Applications of intense low-energy ISOL beams

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NEUTRONS FOR SCIENCE

Potpourri of thoughts on ISOL@MYRRHA

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Optimize event rate

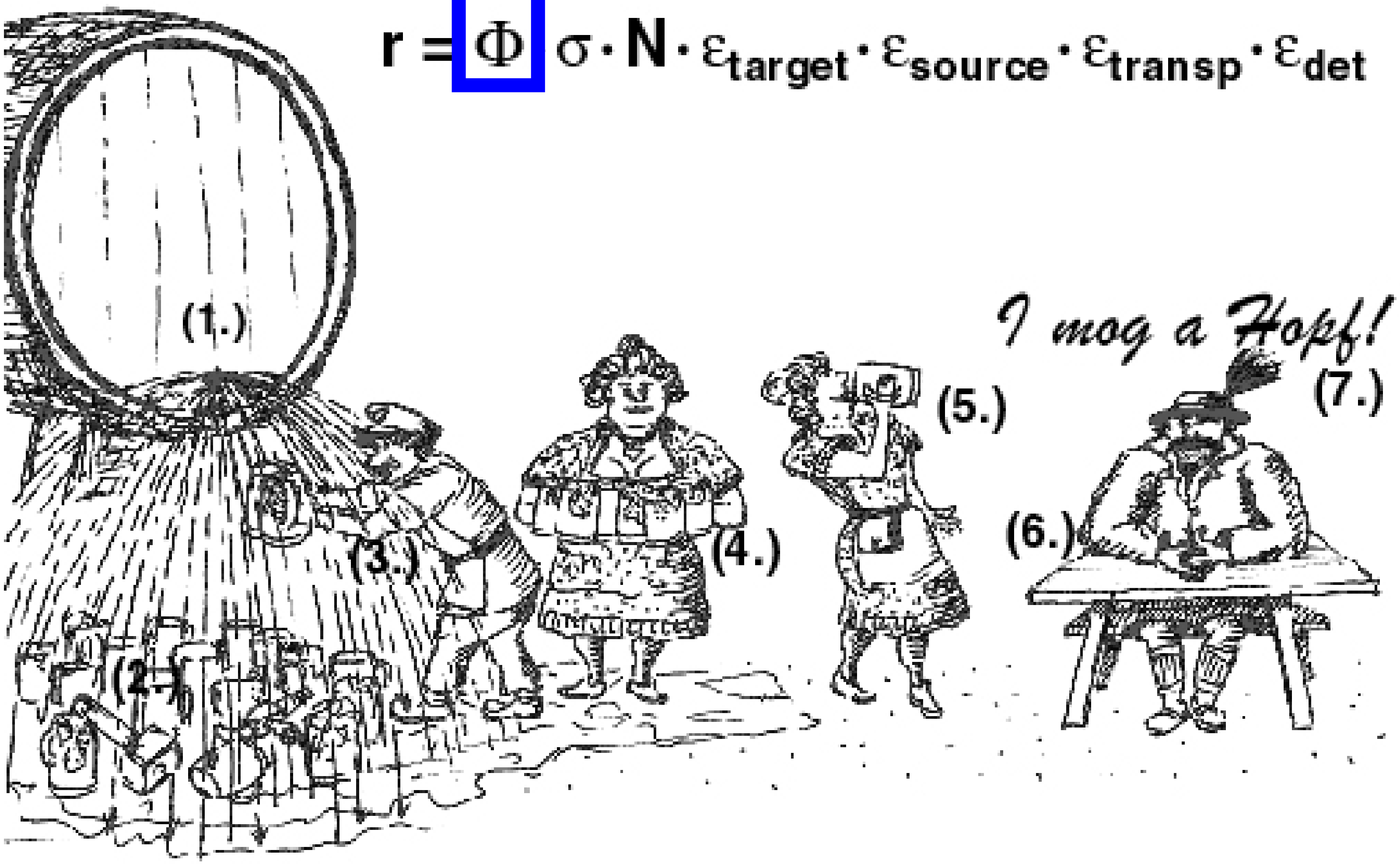
All steps of the separation chain need to be optimized!

$$r = \underbrace{\Phi \cdot \sigma \cdot N}_{\text{In-target production}} \cdot \underbrace{\varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}}_{\text{Efficiency}}$$

Optimize RIB intensity and purity

All steps of the separation chain need to be optimized!

$$r = \boxed{\Phi}\,\sigma \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$



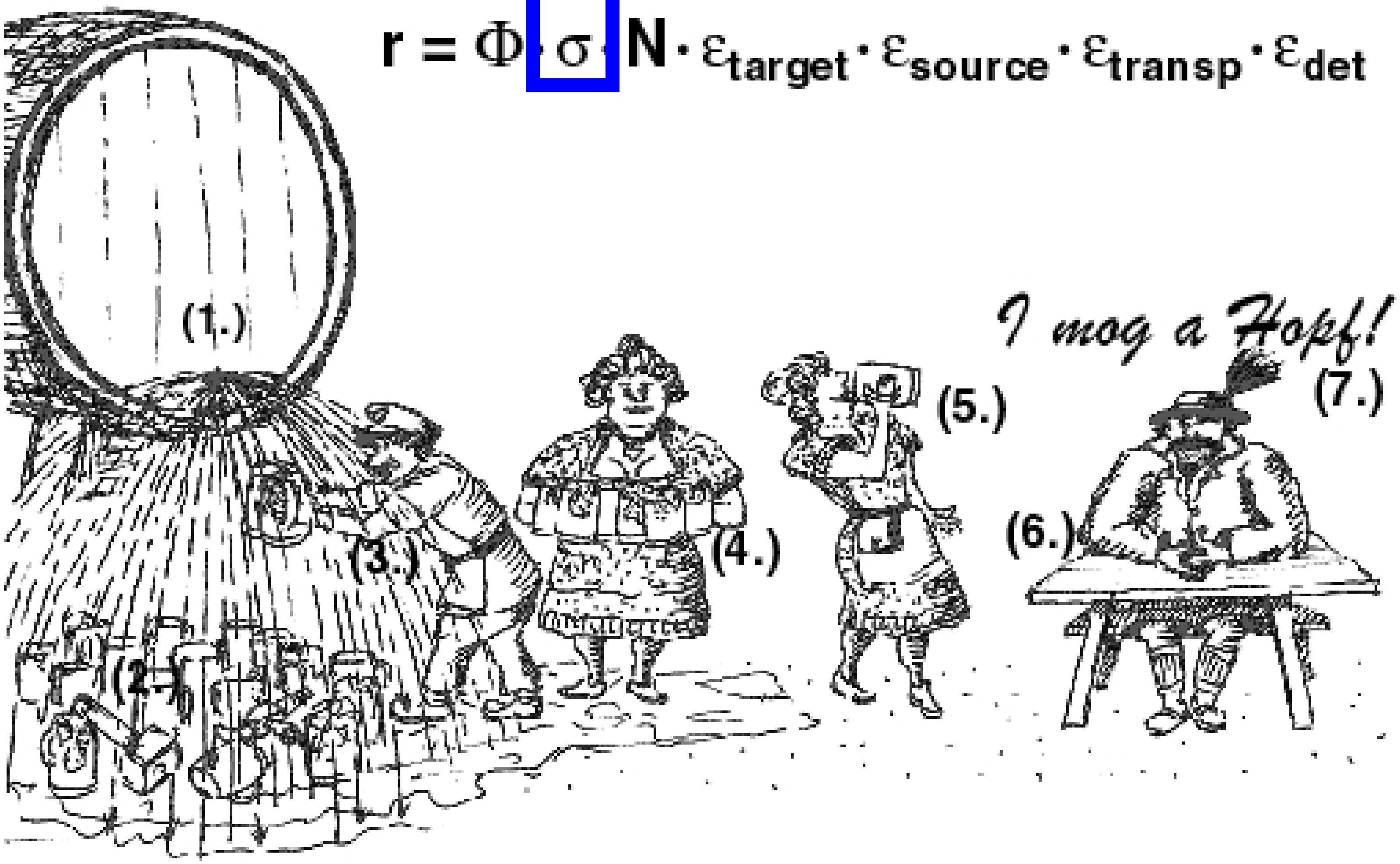
No free beer!

- shielded target station
- target handling (joint use of common hot cell with MYRRHA?)
- handling of volatile radioactivity
- disposal of activated targets
- …
- running costs + personnel

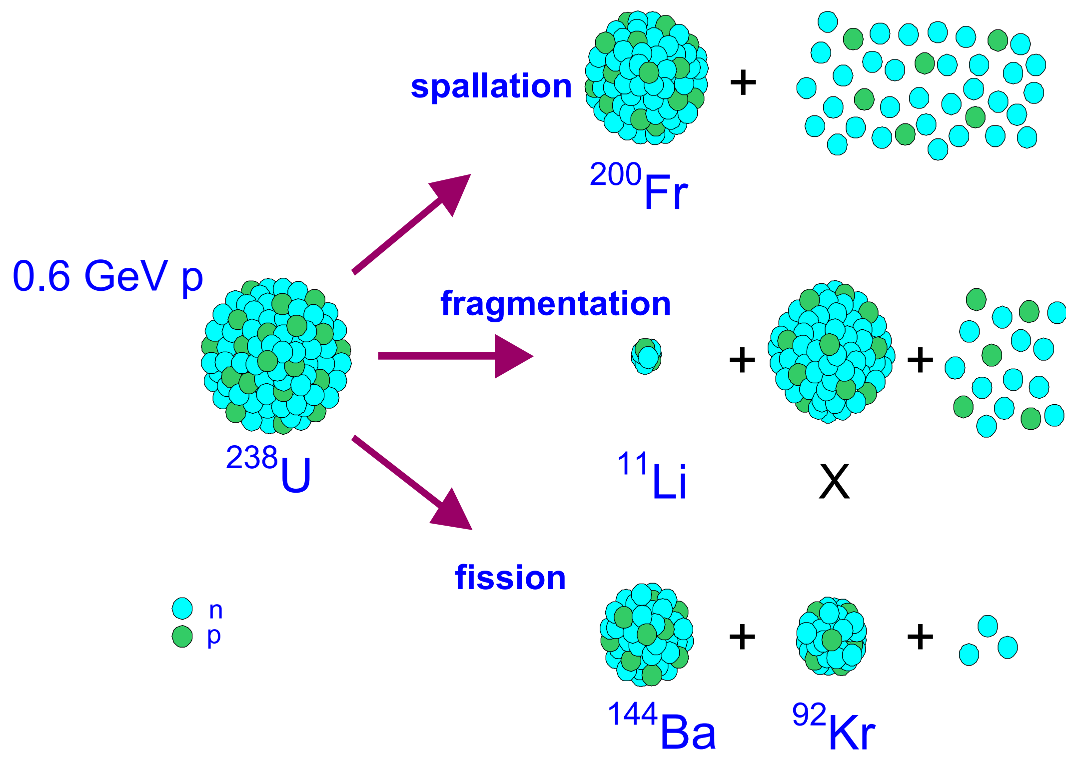
Optimize RIB intensity and purity

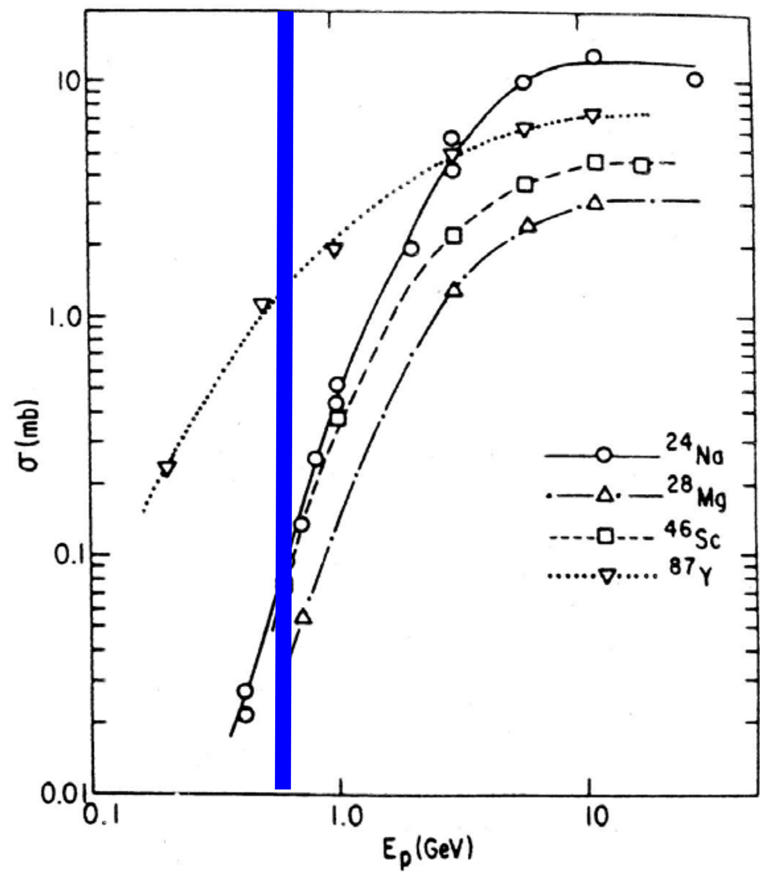
All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \boxed{\sigma} \cdot N \cdot \varepsilon_{target} \cdot \varepsilon_{source} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$



High energy nuclear reactions





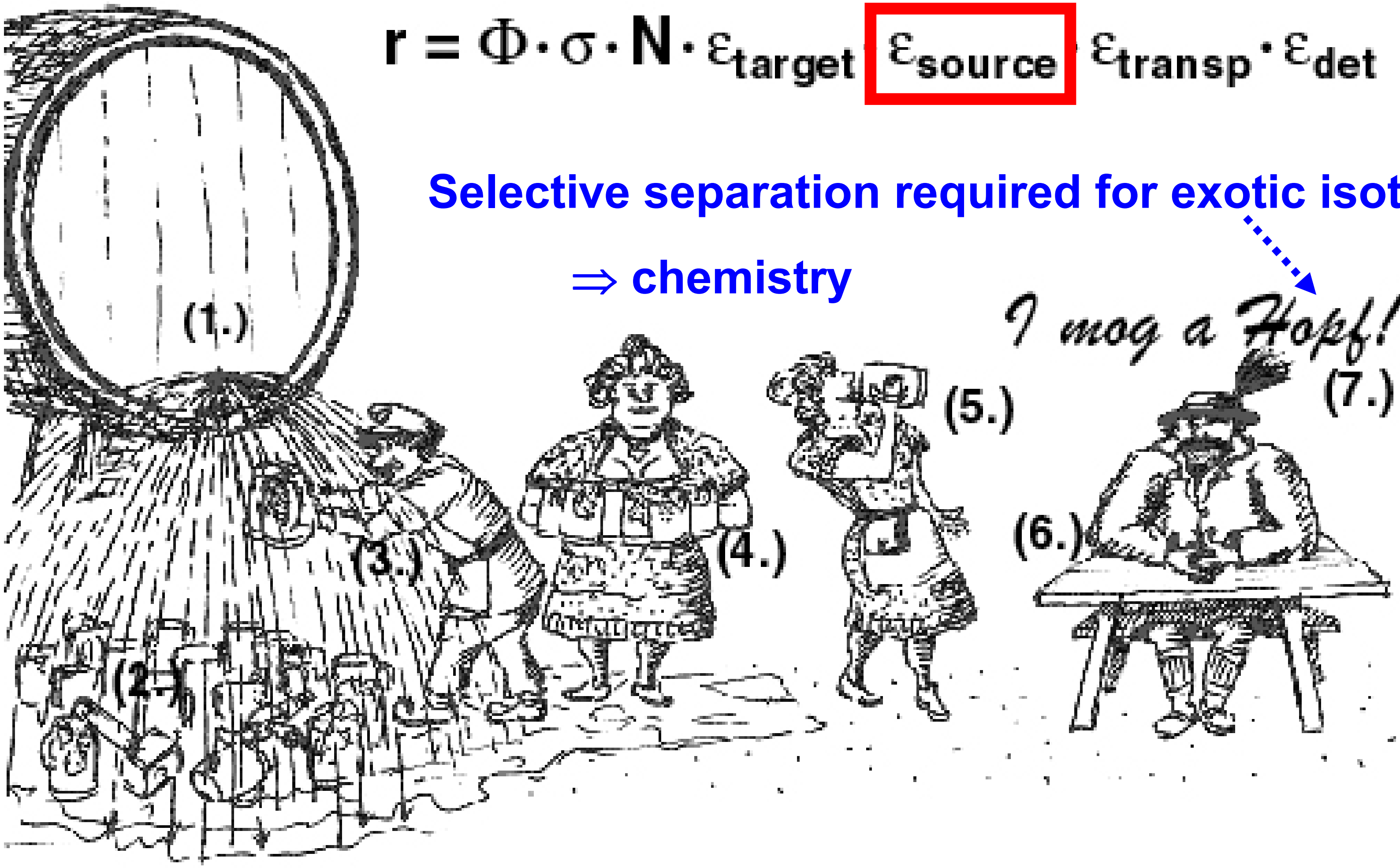
Optimize RIB intensity and purity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{target} \cdot \boxed{\varepsilon_{source}} \cdot \varepsilon_{transp} \cdot \varepsilon_{det}$$

Selective separation required for exotic isotopes!

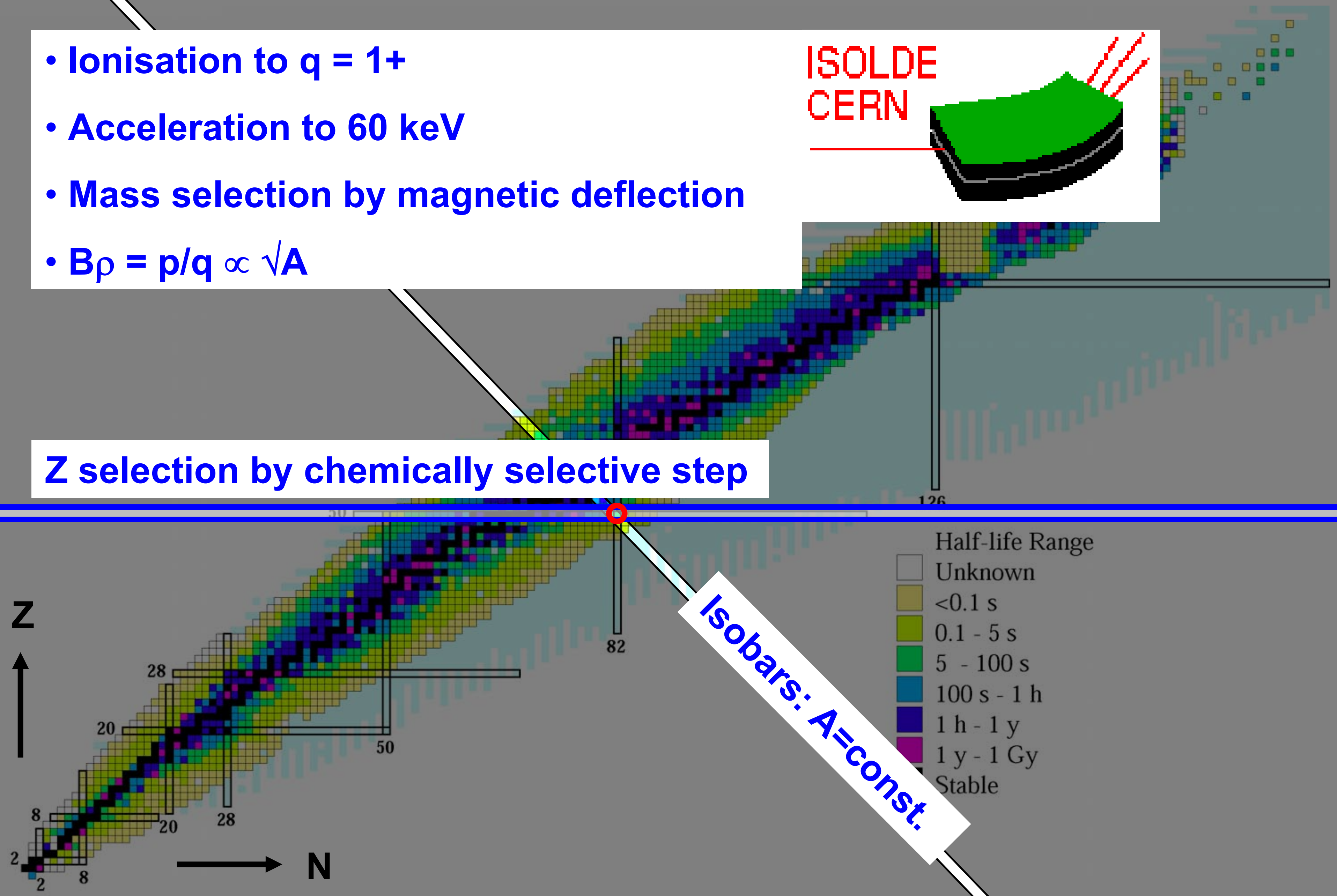
⇒ chemistry



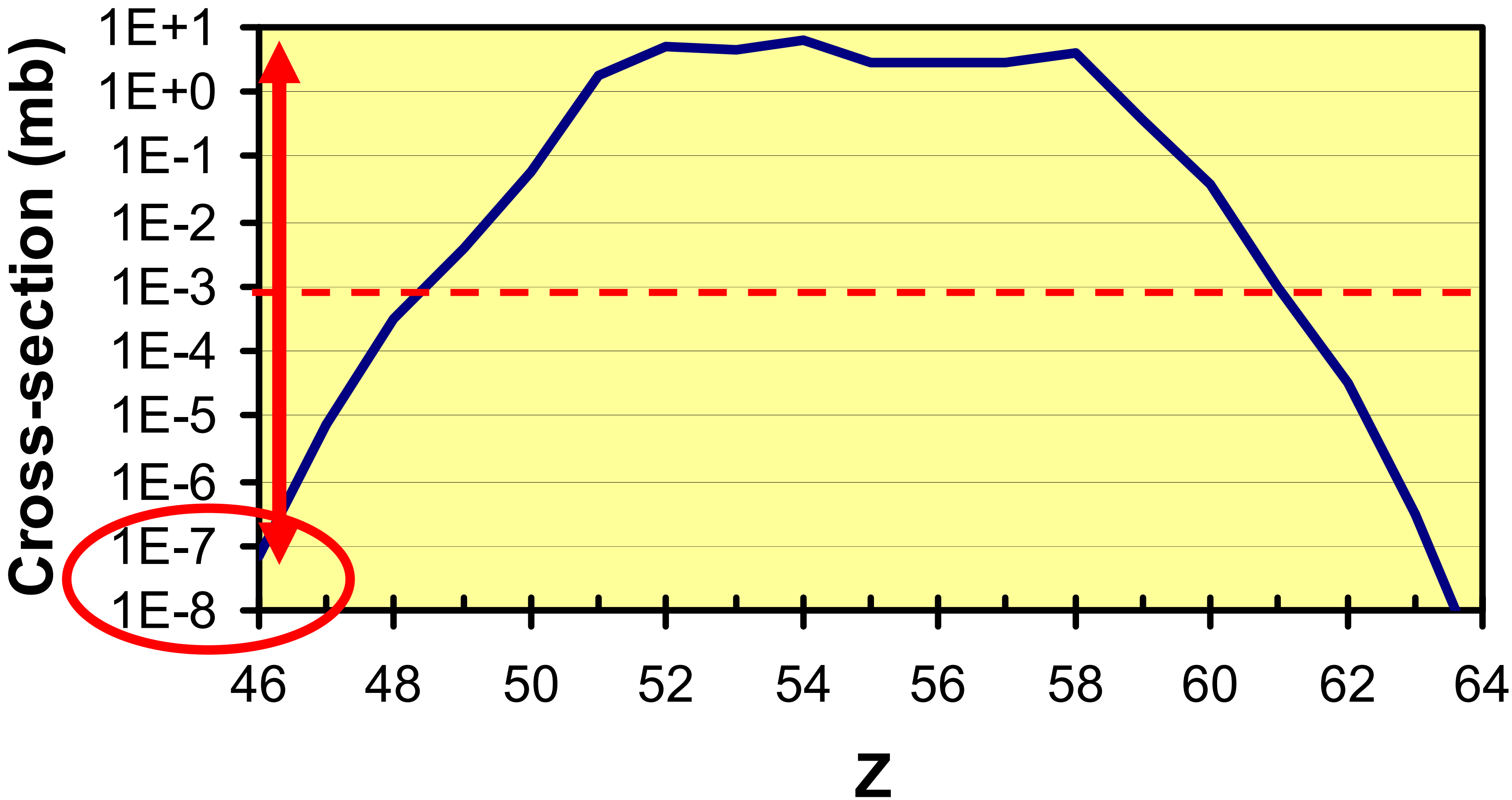
Isotope selection

- Ionisation to q = 1+
- Acceleration to 60 keV
- Mass selection by magnetic deflection
- $B\rho = p/q \propto \sqrt{A}$

Z selection by chemically selective step

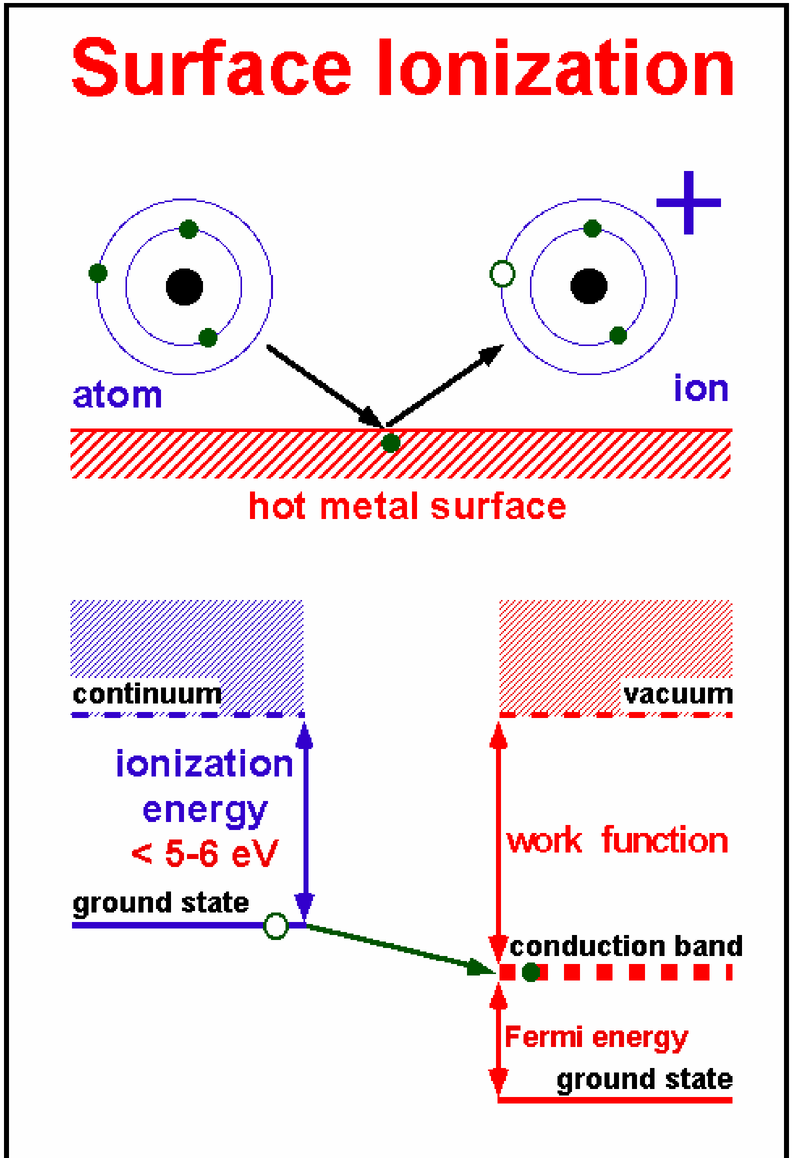


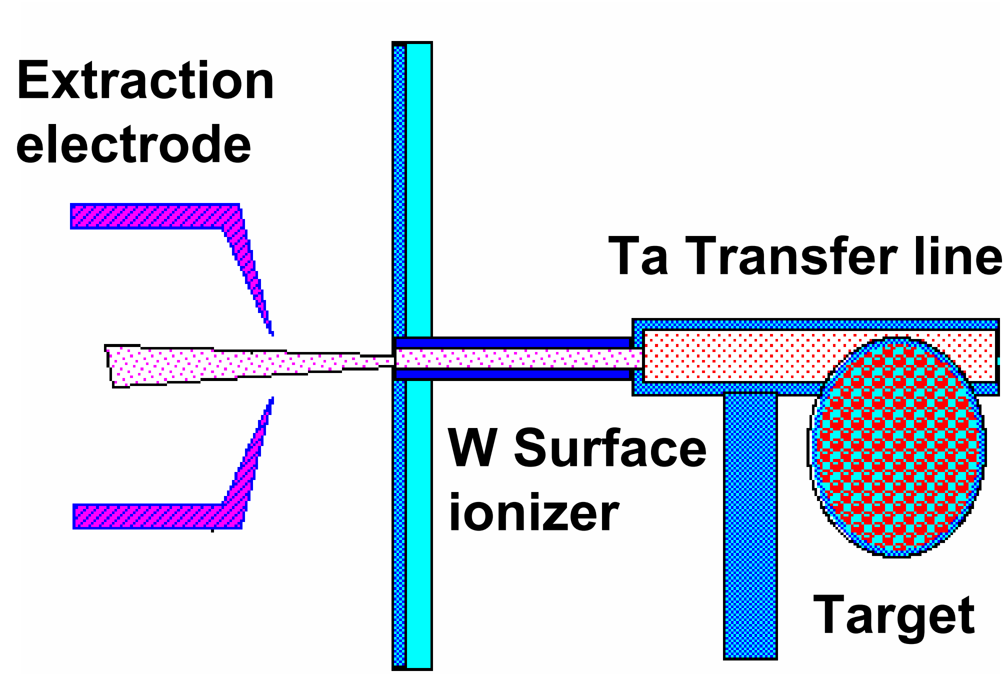
The challenge of the extremes!



1. low cross-sections ⇒ optimize efficiency
2. enormous production of isobars ⇒ optimize selectivity
3. short half-lives ⇒ optimize rapidity

Positive surface ionization source





$$\alpha_s = g_+/g_0 \exp(-(IP - \Phi)/kT))$$

$$\varepsilon_s = \alpha_s / (1 + \alpha_s)$$

Saha-Langmuir equation

ε_s	surface ionization efficiency
Φ	work function of surface
IP	ionization potential of atom
g=2J+1	stat. factor (g_0=2, g_+=1 for alkalis)

Ionization potentials of the elements

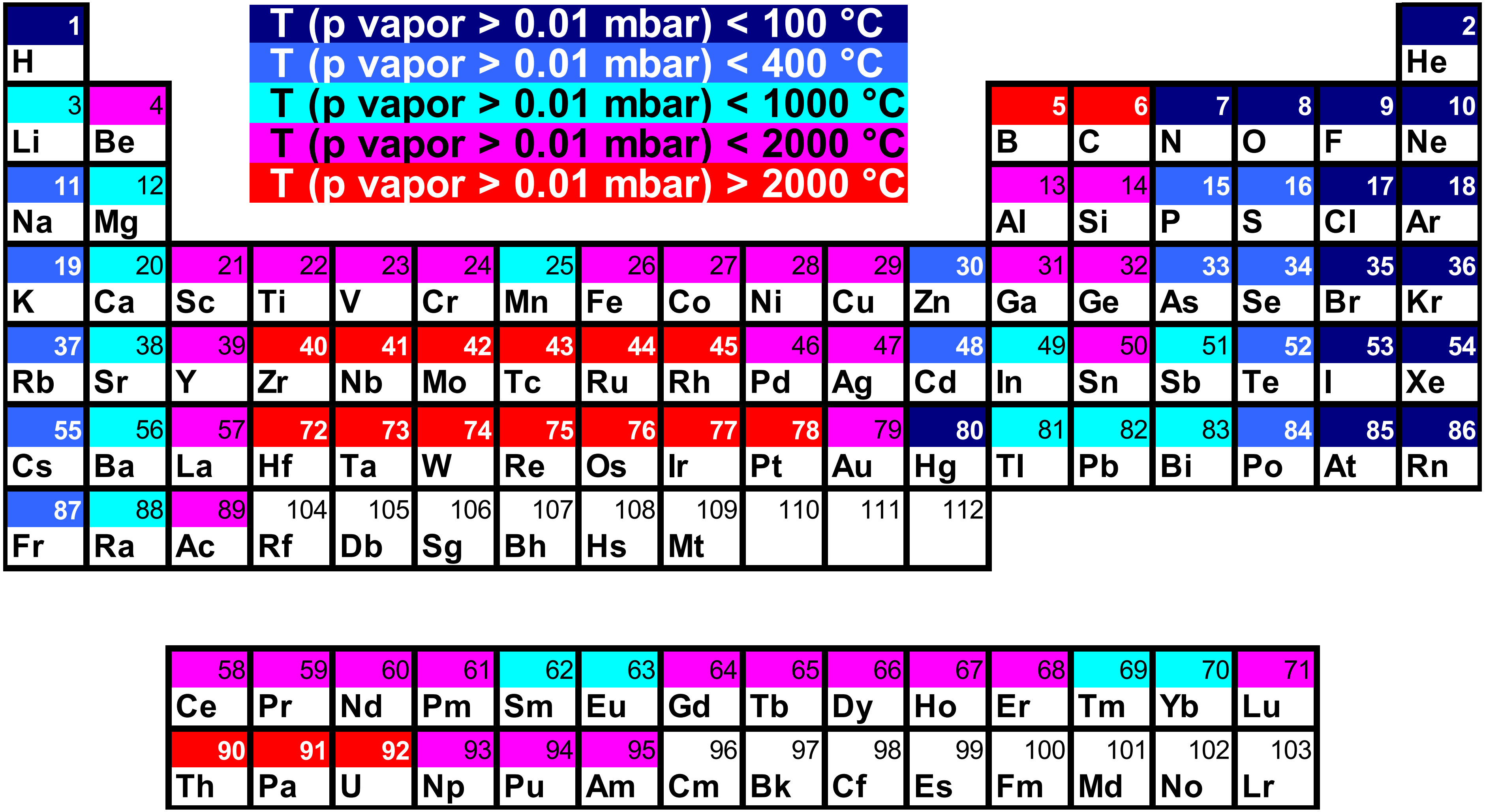
Ionization potential: < 5 eV

Ionization potential: 5.0 - 5.8 eV

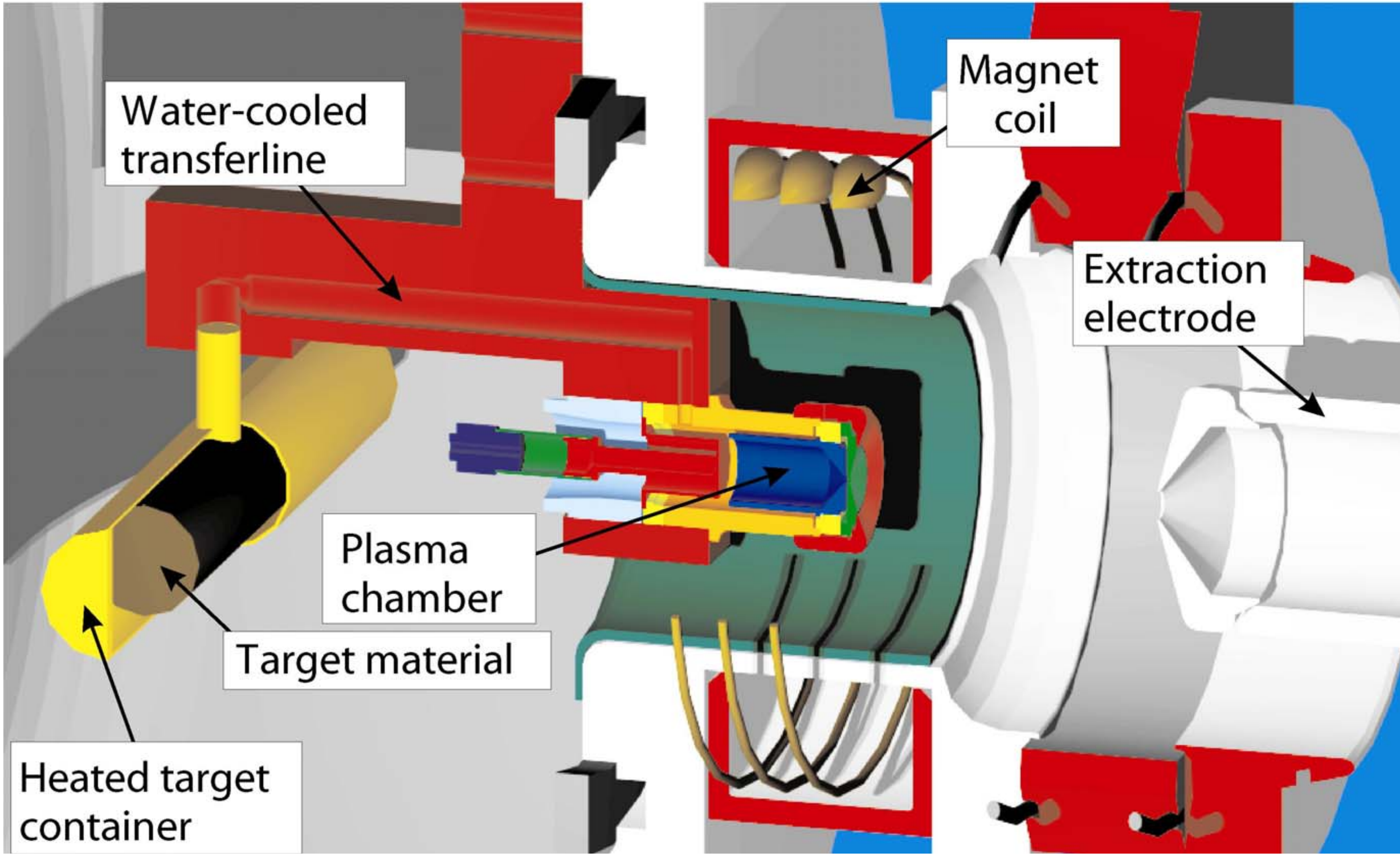
Ionization potential: 5.8 - 6.5 eV

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112						
		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

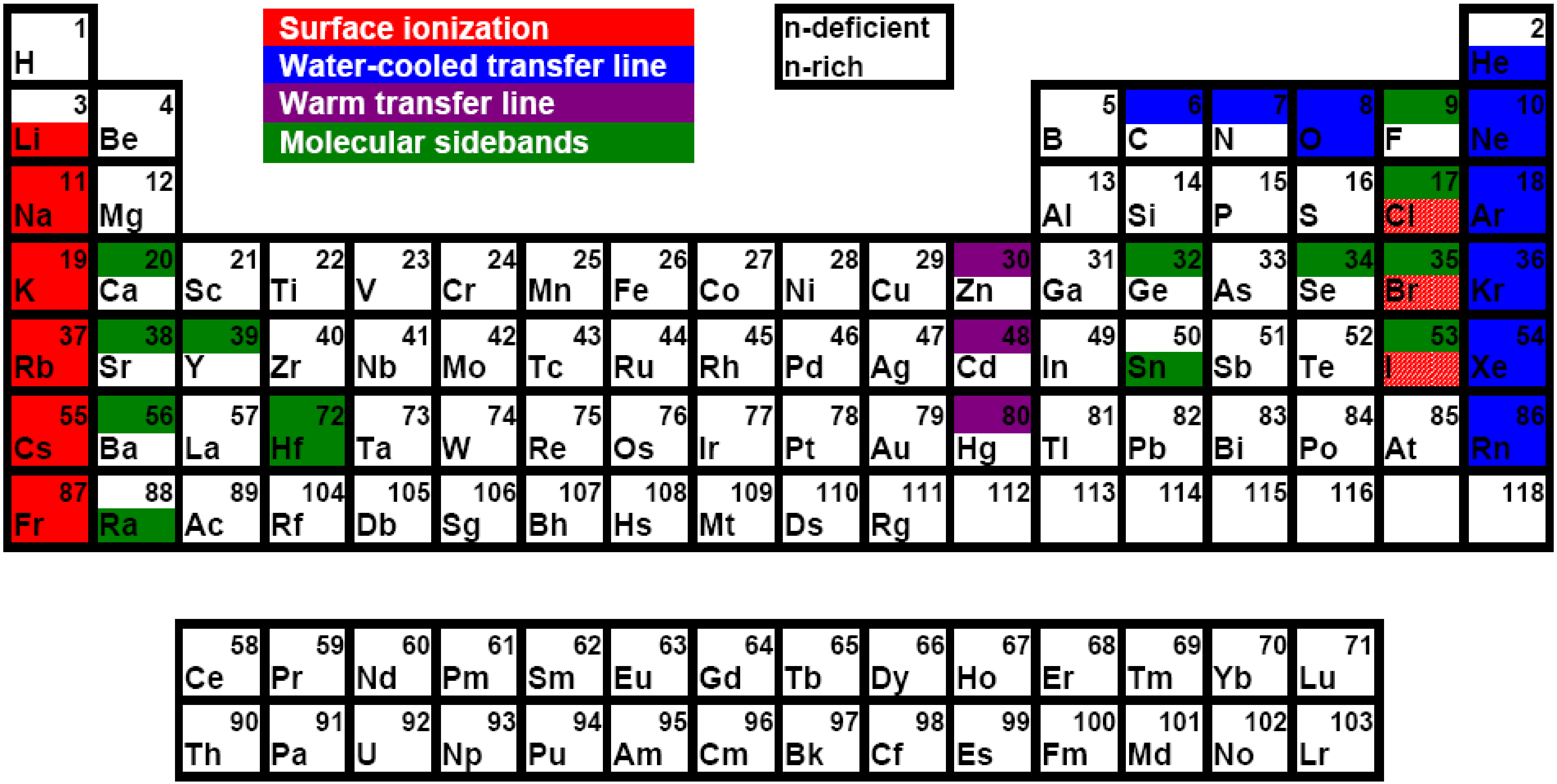
Volatility of the elements



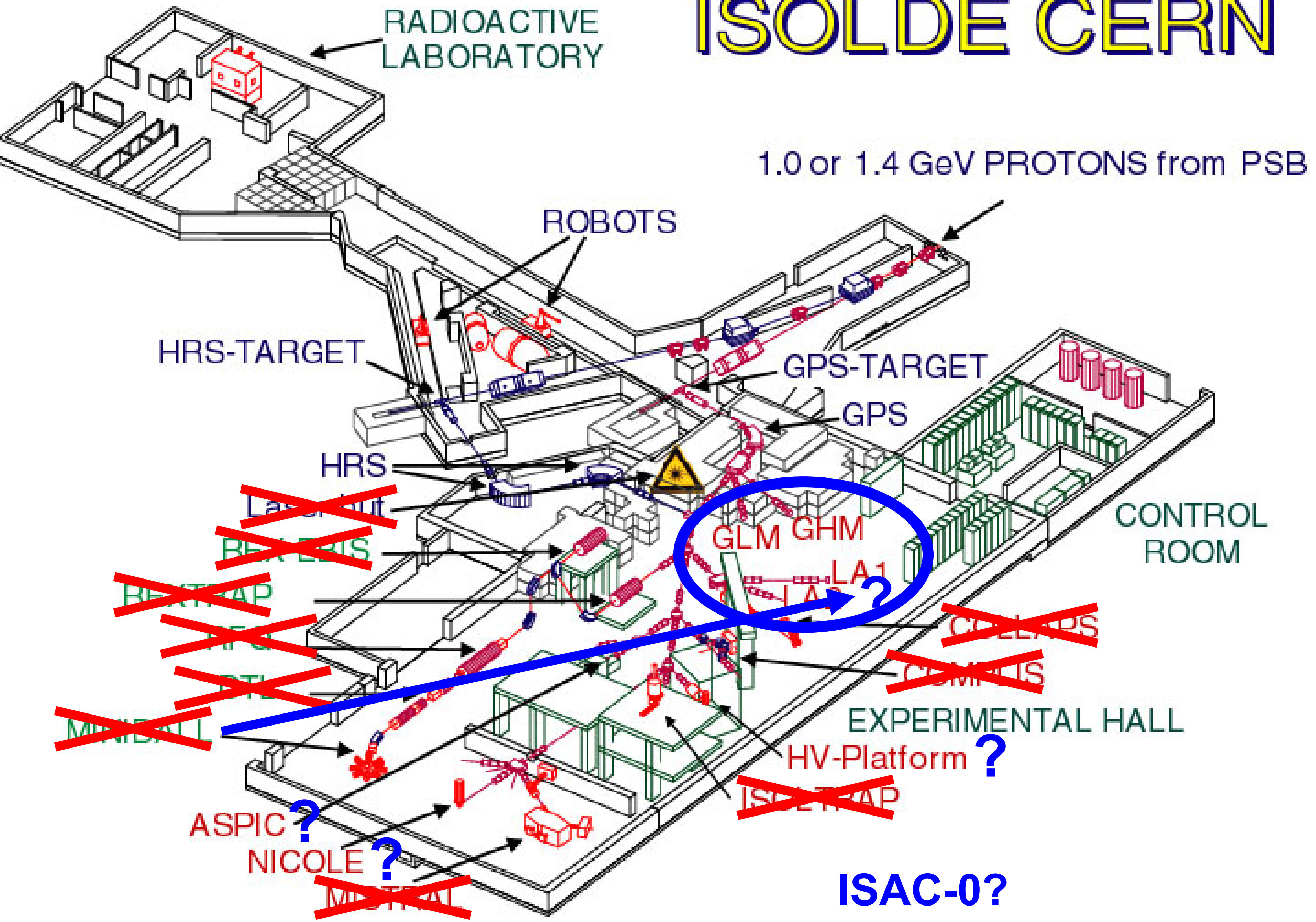
ISOLDE target and ion source unit



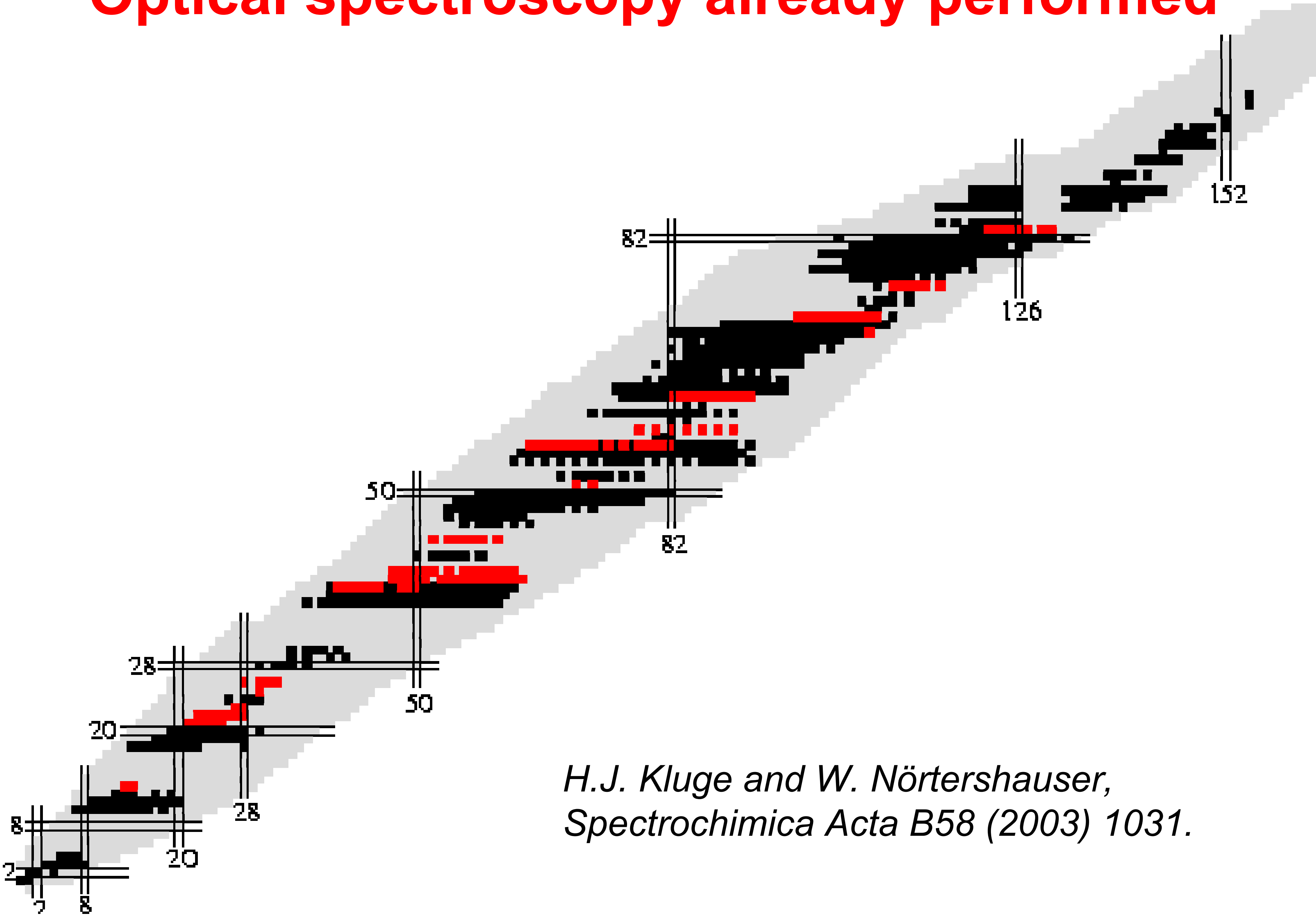
“Pure” ISOL beams without RILIS



ISOLDE CERN


RADIOACTIVE LABORATORY
1.0 or 1.4 GeV PROTONS from PSB
ROBOTS
HRS-TARGET
GPS-TARGET
GPS
HRS
GLM
GHM
LA1
CONTROL ROOM
EXPERIMENTAL HALL
HV-Platform ?
ASPIC ?
NICOLE ?
ISAC-0?

Optical spectroscopy already performed

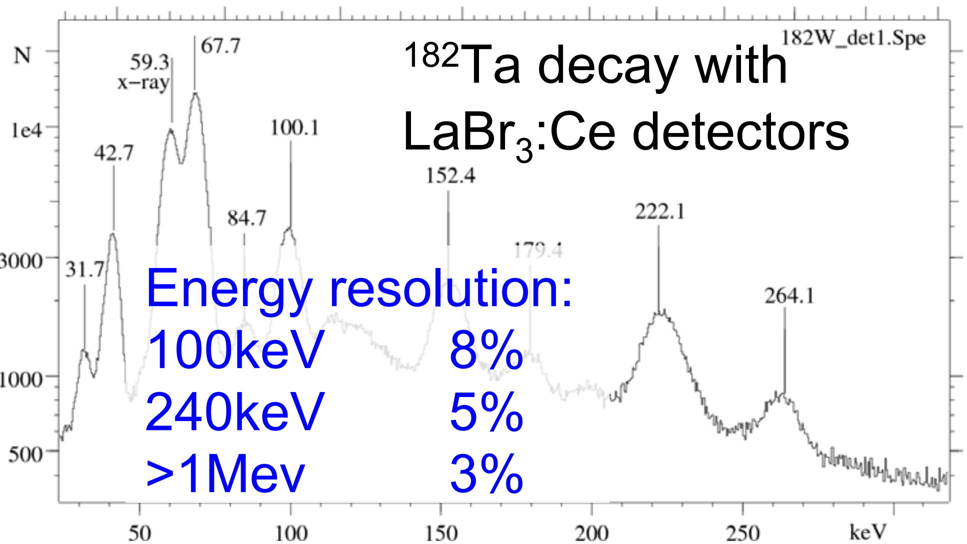


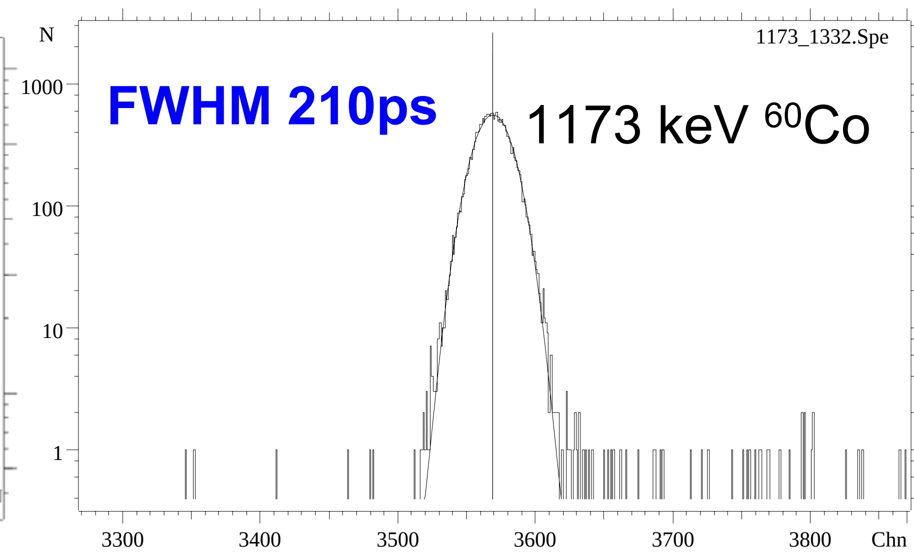
H.J. Kluge and W. Nörtershauser, Spectrochimica Acta B58 (2003) 1031.

Applications in nuclear spectroscopy

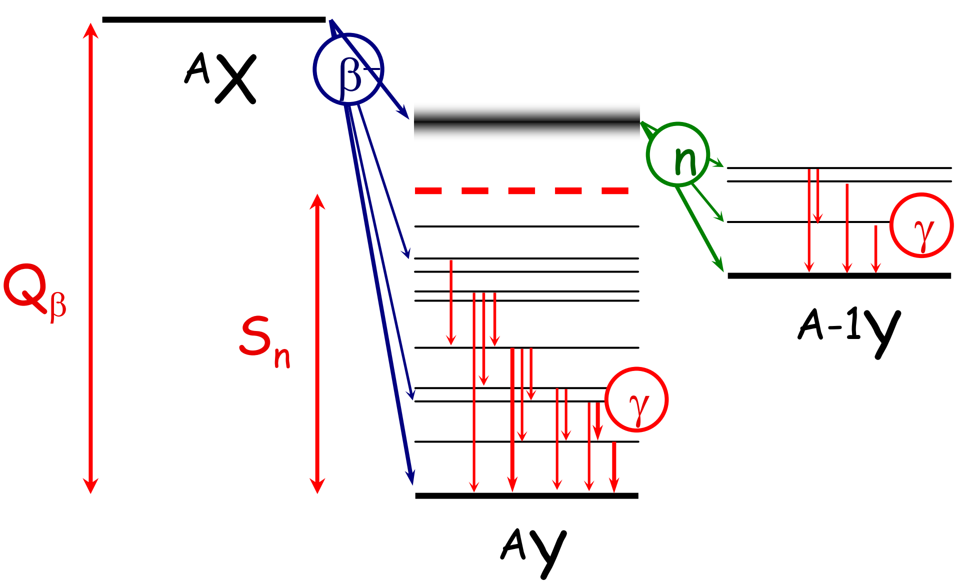
- **most exotic isotopes reachable for few elements only**
- **applications with limited count rate capability or detection methods with high intrinsic selectivity but low efficiency compensated by longer running times:**
  - **fast timing measurements**
  - **E0 transitions with (mini-)orange spectrometer**
  - **beta-delayed neutron spectroscopy with TOF**
  - **superallowed Fermi decays**
  - **crystal spectrometer?**
  - **…**

New and revived nuclear spectroscopy techniques





J.M. Regis et al. (IKP Cologne, ILL)

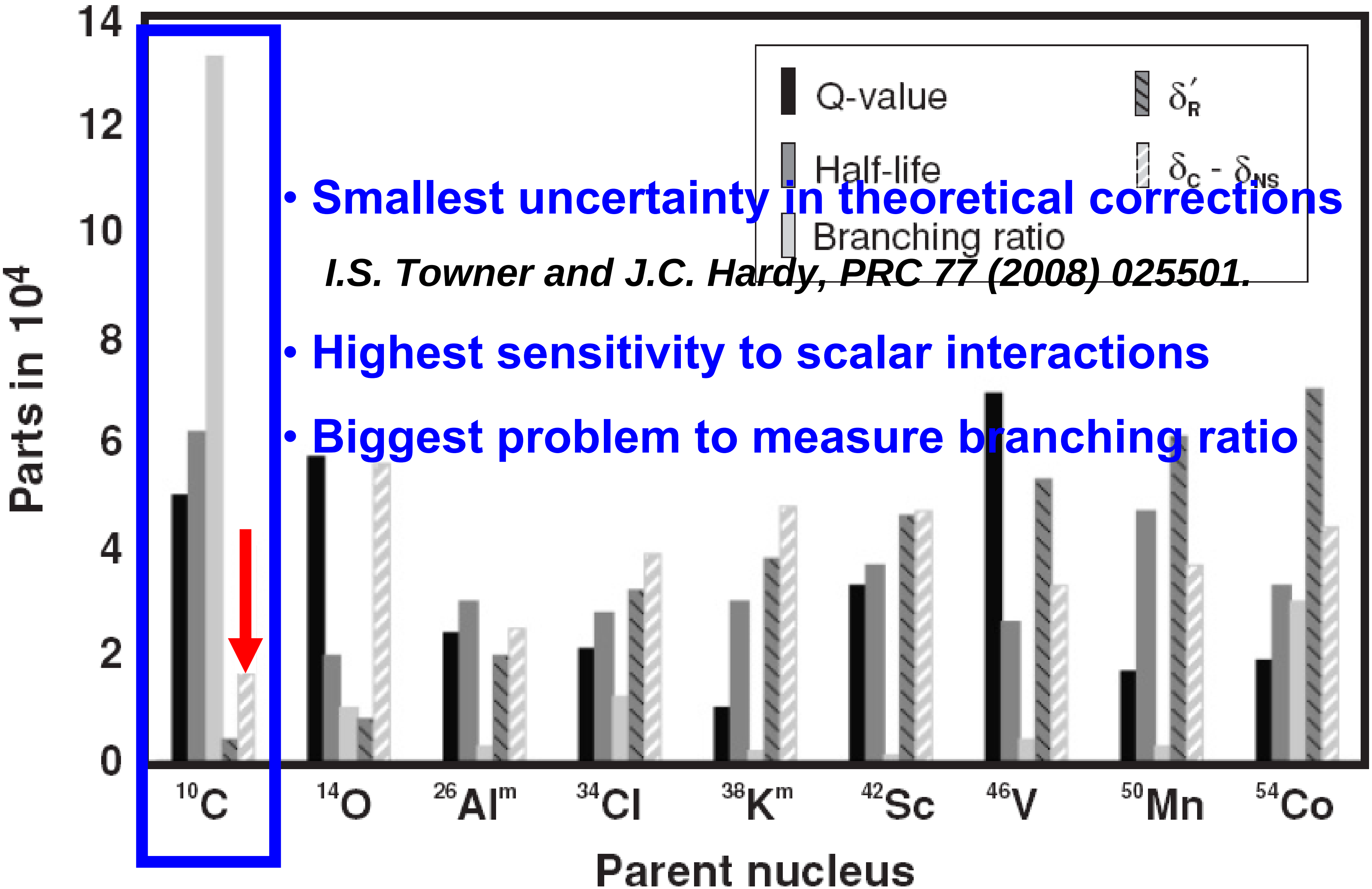


W. Schwerdtfeger et al. (LMU Munich)

Available ISOL beams for $0^+ \rightarrow 0^+$ decay studies

- ^{10}C: 5E5/s as CO, CaO+MK7, ISOLDE@2 uA
- ^{14}O: 4E5/s as CO, SiC+MK11, ISAC@75 uA
- ^{18}Ne: 1E6/s, CaO+MK7, ISOLDE@2 uA or
  8E6/s, SiC+MK11, ISAC@75 uA
- ^{26m}Al: 4E5/s, SiC+Re SI, ISAC@70uA
- ^{34}Ar: 3E6/s, CaO+MK7, ISOLDE@2uA
- ^{38m}K: 7E7/s, TiC+Re SI, ISAC@40uA
- ^{38}Ca: 6E3/s as CaF^+, Ti+W SI, ISOLDE@2uA
- ^{62}Ga: 1E4/s, ZrC+TRILIS, ISAC@35 uA
- ^{74}Rb: 1E4/s, Nb+Re SI, ISAC@10 uA
- ^{98}In: <<1/s with present target technology

Status of superallowed Fermi decay

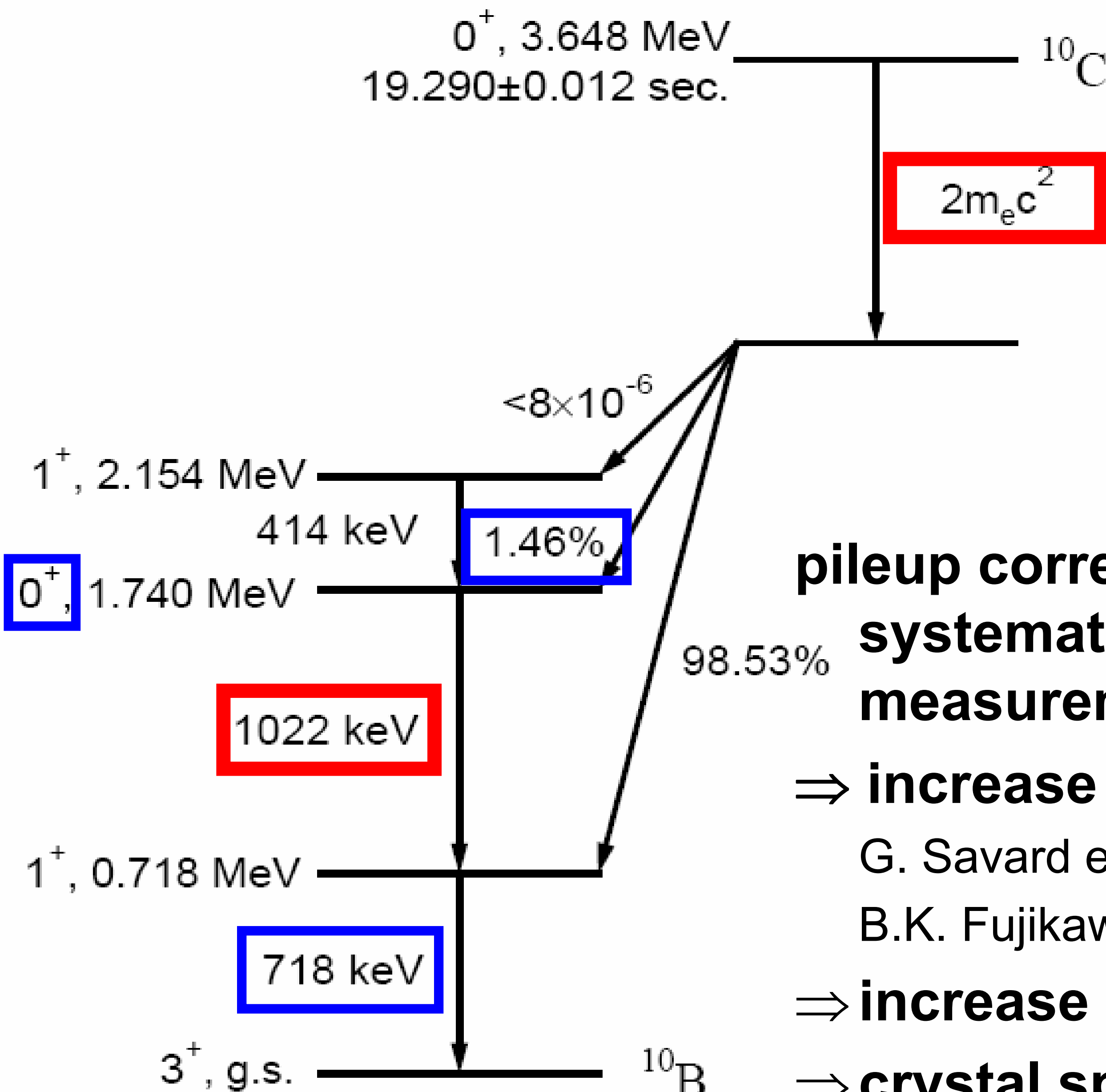


- **Smallest uncertainty in theoretical corrections**

I.S. Towner and J.C. Hardy, PRC 77 (2008) 025501.

- **Highest sensitivity to scalar interactions**
- **Biggest problem to measure branching ratio**

Branching ratio measurement in ^{10}C decay



pileup corrections dominate systematic error on B.R. measurements

⇒ **increase number of detectors**

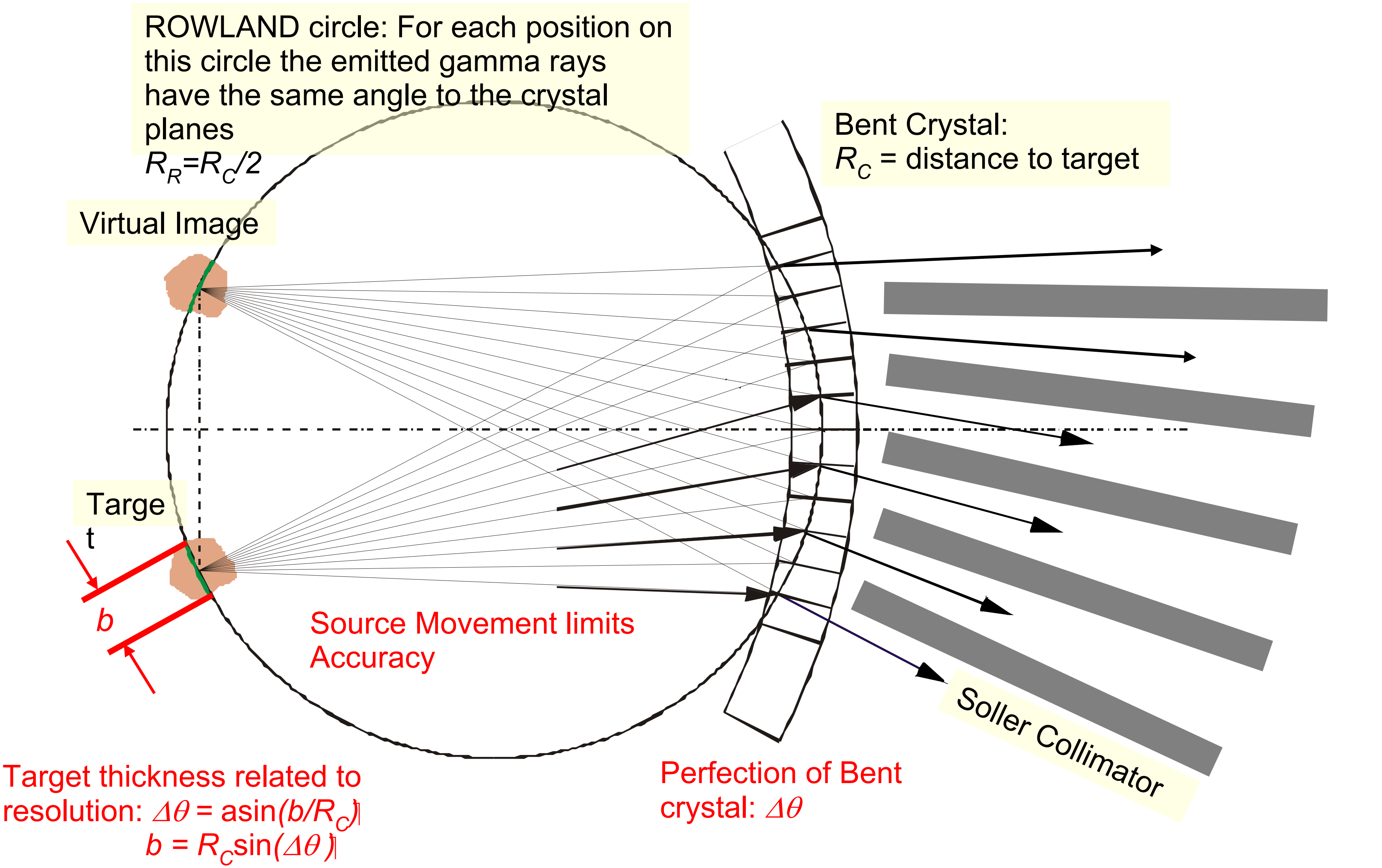
G. Savard et al., PRL 74 (1995) 1521.

B.K. Fujikawa et al., PLB449 (1999) 6.

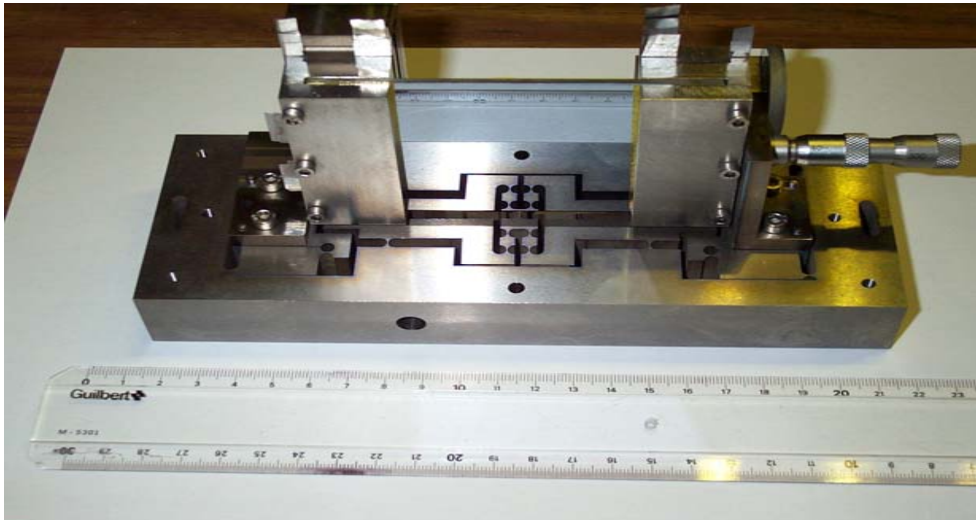
⇒ **increase experiment duration**

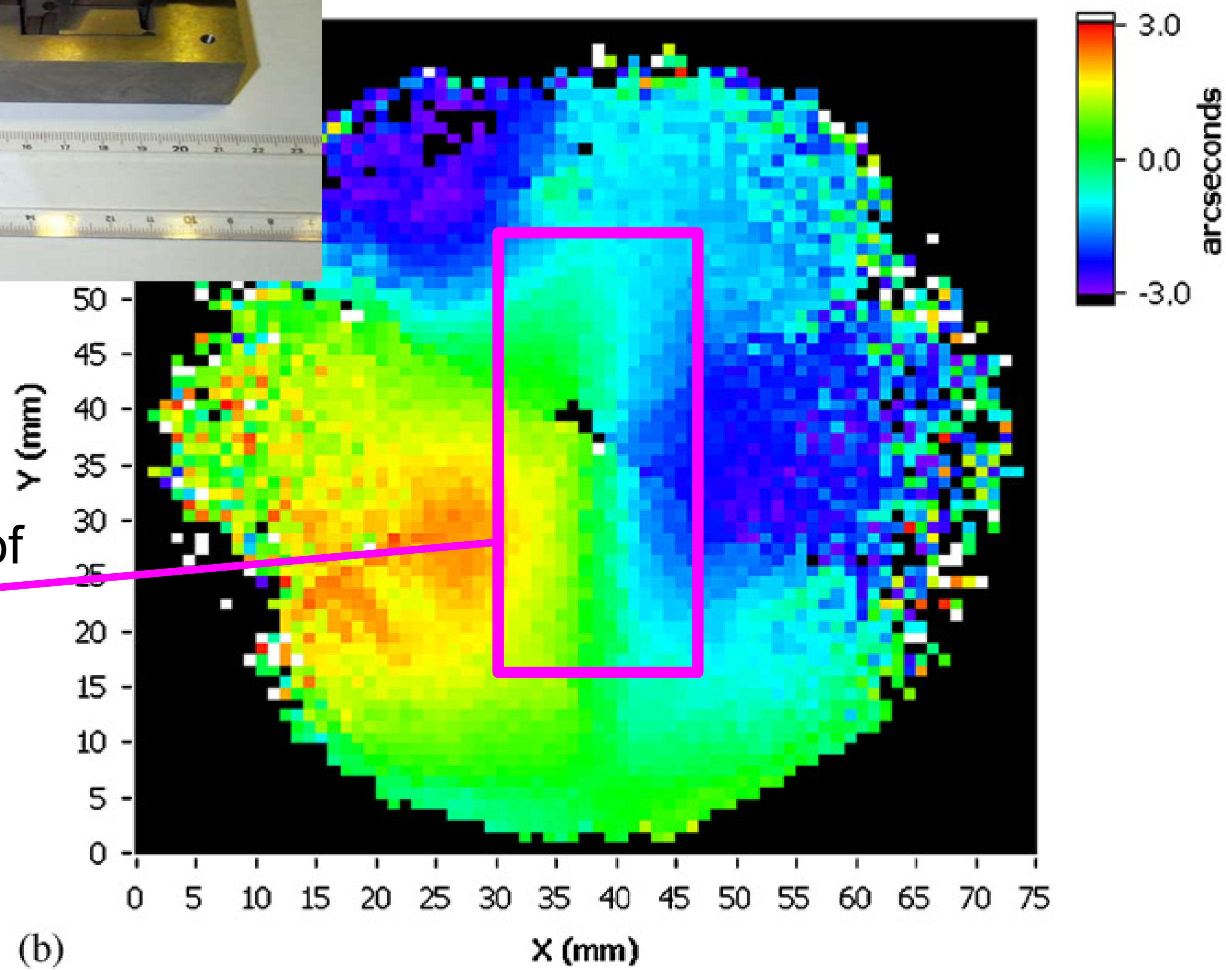
⇒ **crystal spectrometer??**

Dumond Geometry: Curved Crystal Spectrometer (High Resolution with Divergent Gamma Rays)



How perfect can we curve a crystal ?





(b)

Resolution within an area of <u>10 x 40 mm</u>: 2 arcsec

Solid Angle: 10^{-7}

Resolution of a Single Crystal Spectrometer

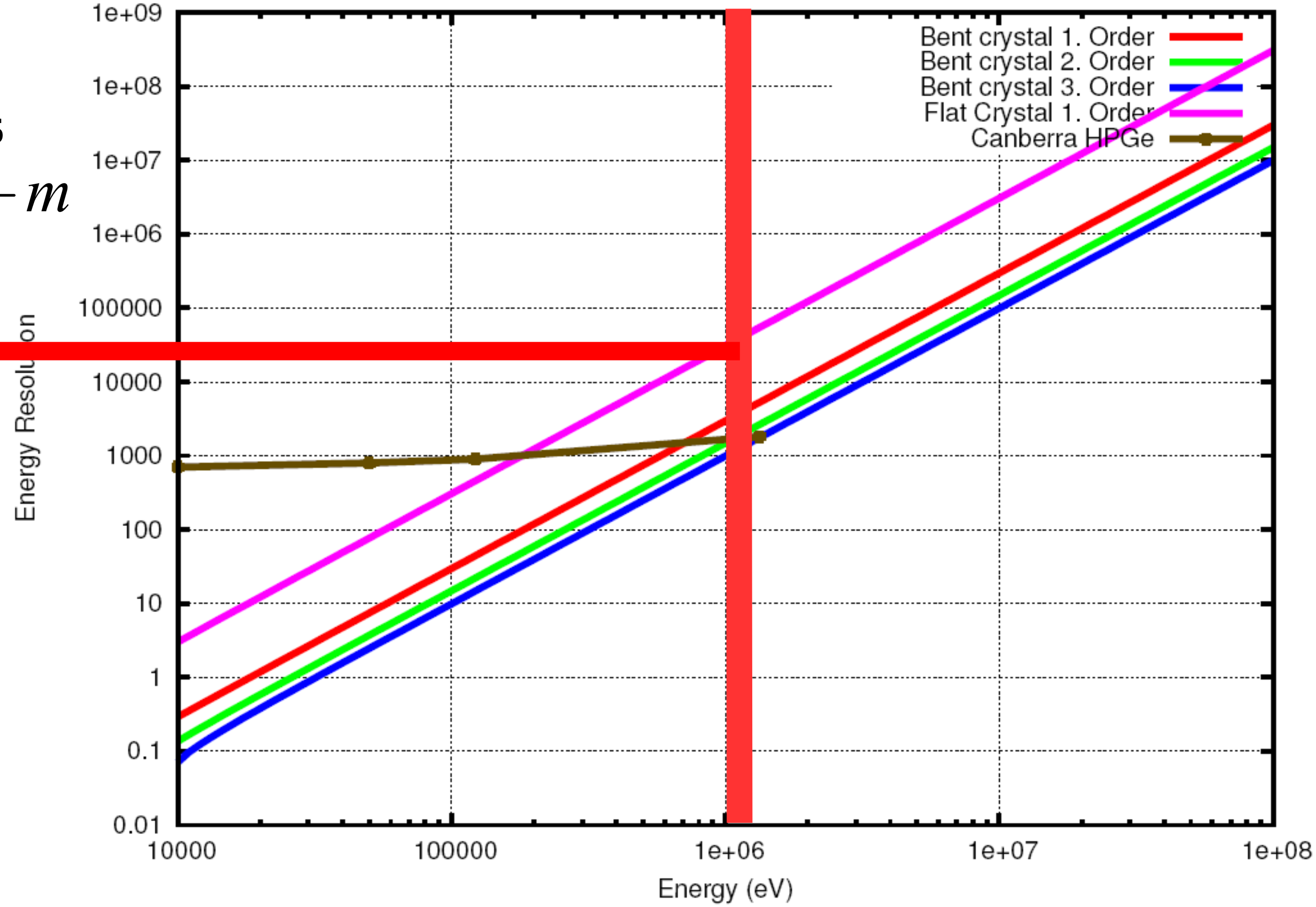
Braggs Law: $n\lambda = 2d\sin(\theta_n) \rightarrow$ Discrimination of Energies by Bragg Angles

$$d \approx 10^{-10}\, m$$

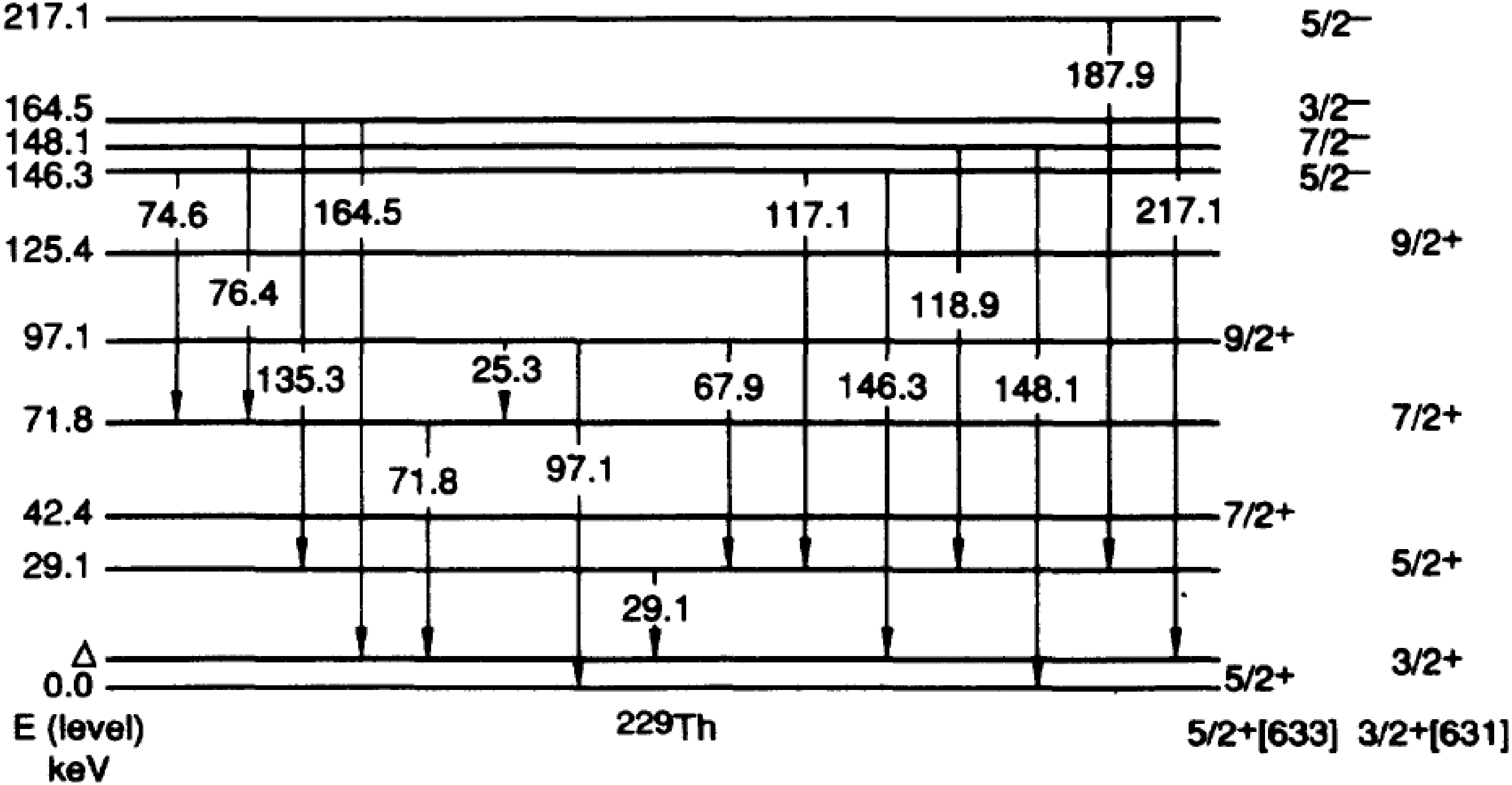
$$\lambda = \frac{h \cdot c}{E_\gamma} \cong \frac{1 \cdot 10^{-6}}{E_{[eV]}}\, m$$

For E < 1MeV Crystal Spectrometers have best possible Energy Resolution!

For complete Spectroscopy additional Detectors are needed!



The low-energy isomer in ^{229}Th

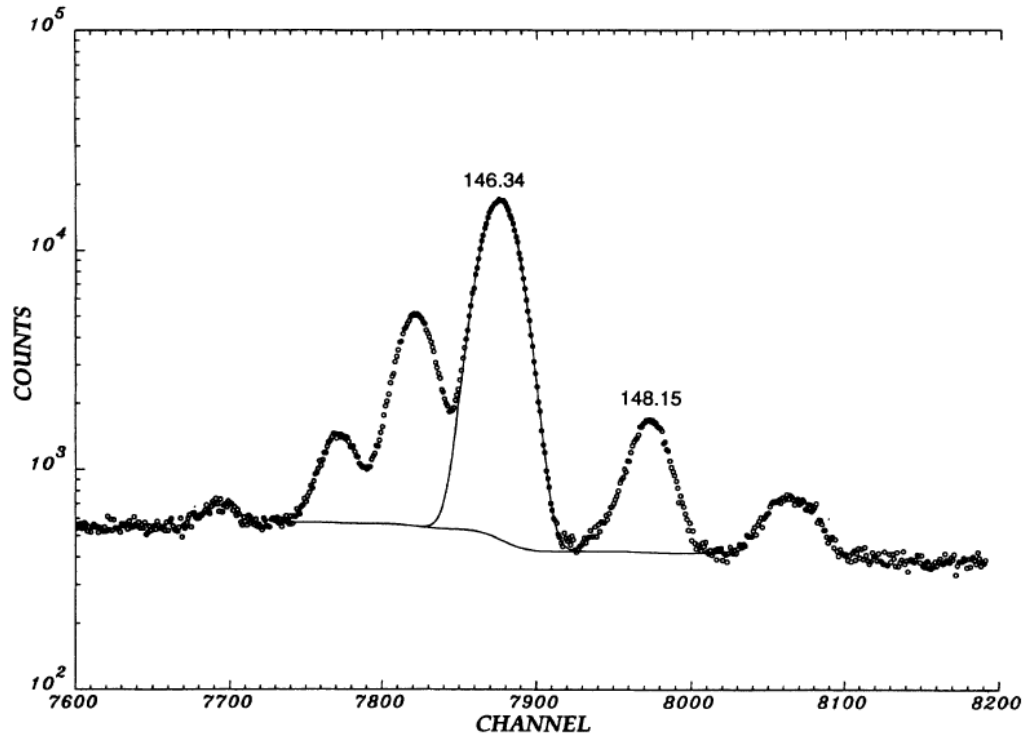


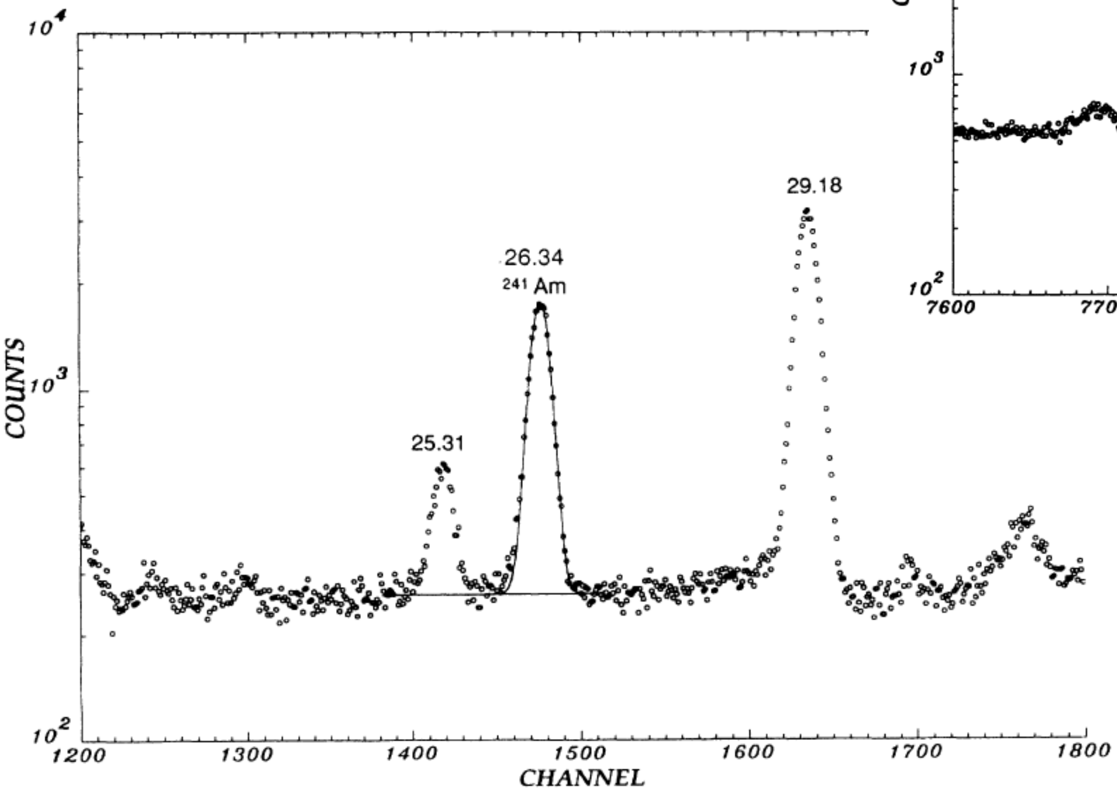
R.G. Helmer and C.G. Reich, PRC 49 (1994) 1845.

^{229m}Th measured with Ge detectors

FWHM = 270-900 eV

Δ = 3.5(10) eV





R.G. Helmer and C.G. Reich, PRC 49 (1994) 1845.

^{229m}Th measured with X-ray micro-calorimeter

FWHM = 26 eV

Δ = 7.6(5) eV

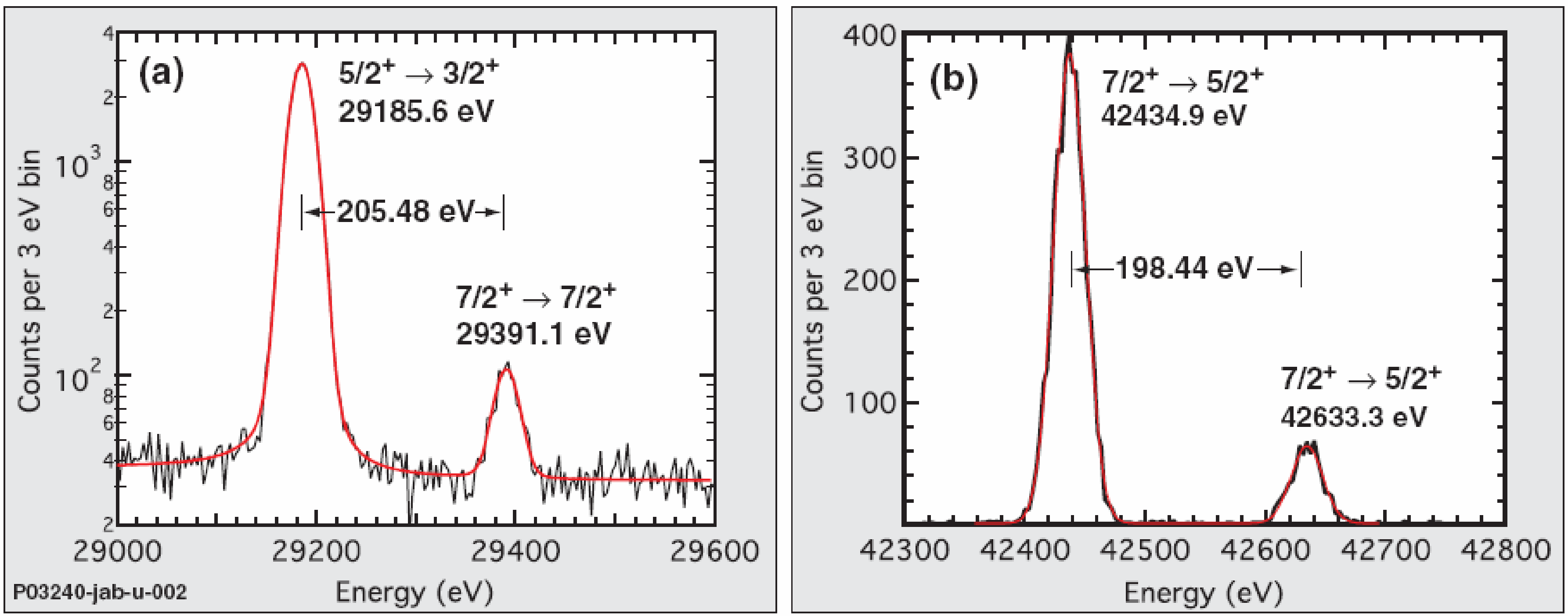


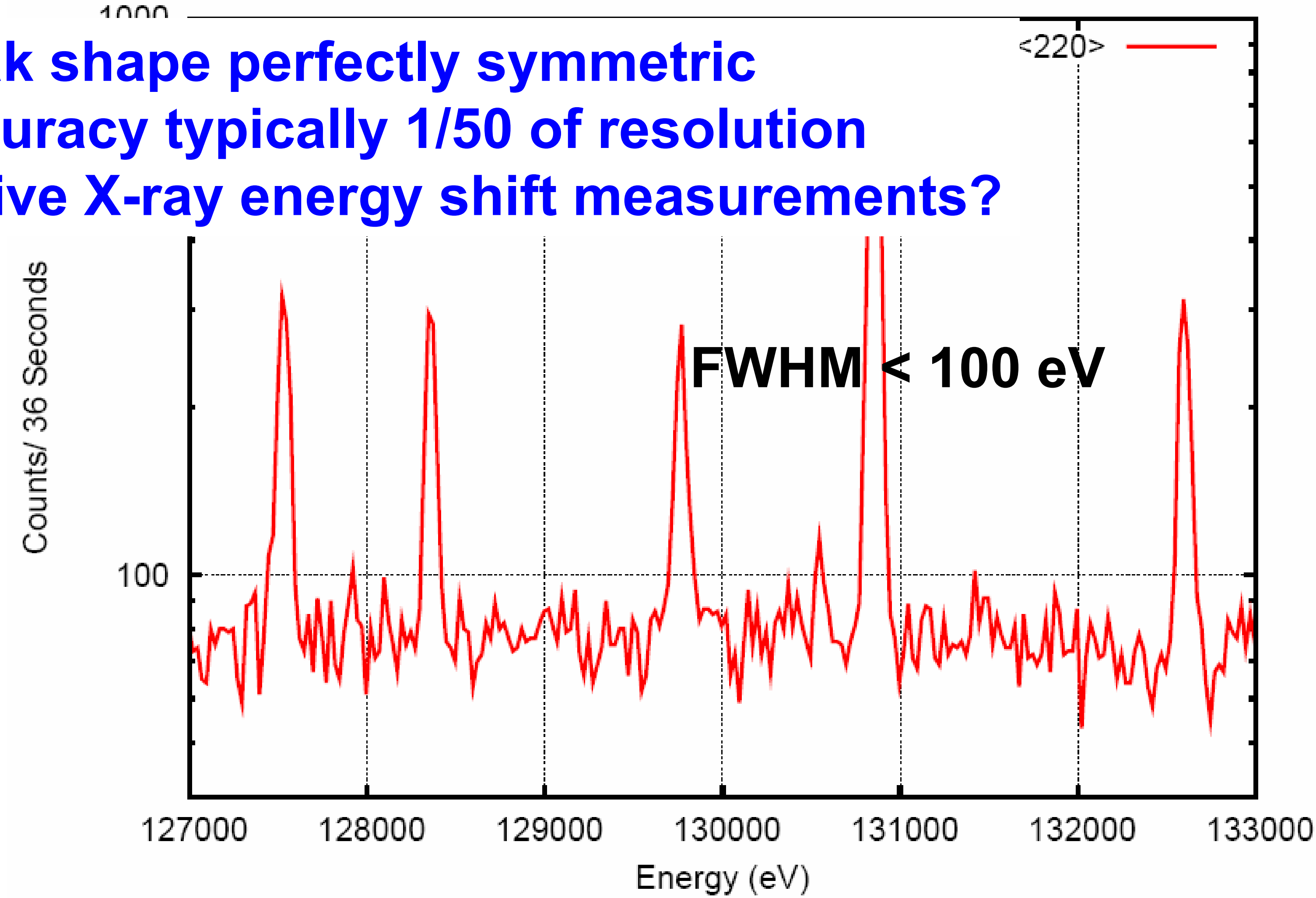
FIG. 2 (color). XRS spectra in the 29 and 42 keV energy regions. Data illustrated for the 29 keV doublet (ΔE_{29}) is the sum of 11 data sets and 25 pixels (a), and data illustrated for the 42 keV doublet (ΔE_{42}) represents the sum of 11 data sets only for pixel 0 (b). Black lines represent the data; red lines represent the least-square fitting results. Full-energy peaks are labeled by J^{π} of the corresponding ^{229}Th transition.

B.R. Beck et al., PRL 98 (2007) 142501.

Measure ^{229m}Th with bent crystal spectrometer

FWHM = 1-20 eV (third order)

- peak shape perfectly symmetric
- accuracy typically 1/50 of resolution
- revive X-ray energy shift measurements?



EDM Probes of New CP Violation

f	d_{SM}	d_{exp}	d_{future}
e^-	< 10[illegible]	$< 1.6 \times 10^{-27}$	$\rightarrow 10^{-31}$
n	[illegible]	[illegible]$\times 10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg	$< 10^{-33}$	$< 2.1 \times 10^{-28}$	$\rightarrow 10^{-32}$
μ	[illegible]	[illegible]	$\rightarrow 10^{-24}$

Yale, Indiana, Amherst

ILL, PSI, SNS,…

TRIUMF, KVI, ANL, Princeton…

Also ^{225}Ra, ^{129}Xe, d

BNL

About half a dozen neutron EDM experiments under operation or preparation!

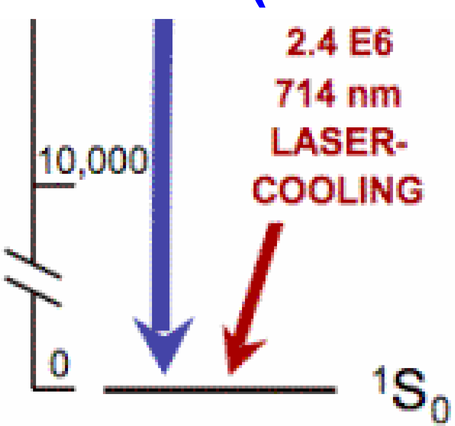
MOT

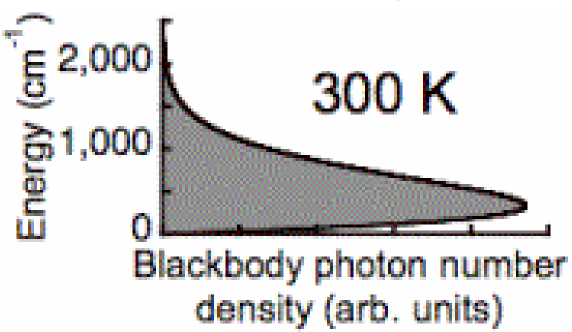
Precision experiments with neutral atom traps:

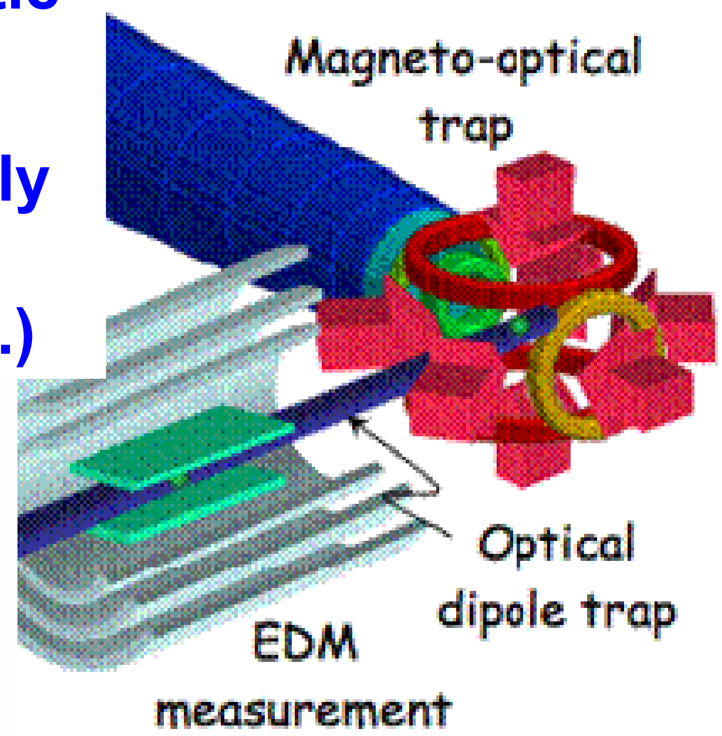
- **have intrinsically low efficiency**
- **require long time to optimize all components and minimize systematic uncertainties**
- **use elements that coincide perfectly with those provided by "simple" ion sources (alkali metals, noble gases..)**

J.R. Guest et al.,

PRL 98 (2007) 093001.







Cancer

About 1 000 000	new cancer cases per year in EU
	58 % local disease, 42 % generalized
45 %	cured (5 year survival)

22 %	surgery alone
12 %	radiation therapy
6 %	combination surgery + radiation
5 %	chemo-therapy
just beginning of	systemic radionuclide therapy

HOW: expose cancer cells or cancer tissue to sufficient radiation doses?

ISOTOPES in Therapy =

surgery with radiation

	Gamma Knife	ß-Knife	α-Knife	Auger Knife
ISOTOPE	^{60}Co E_γ > 1 MeV	^{131}I, ^{90}Y, ^{153}Sm, ^{166}Ho, Others $E_ß$ 1 – 3 MeV	$^{212, 213}Bi$, ^{211}At, ^{149}Tb, $^{223, 224}Ra$ E_α 4–8 MeV	^{125}I ^{165}Er E_e few eV
Range	Full body penetration	**about** 1 cm	30 – 80 µm	1 µm
Application	Brain cancer,..	**Radio-immuno therapy: Lymphoma..**	Leukemia, Lymphoma, metastases	future
	Tissue surgery ex vivo	Tissue surgery in vivo	Cell surgery	Molecular surgery

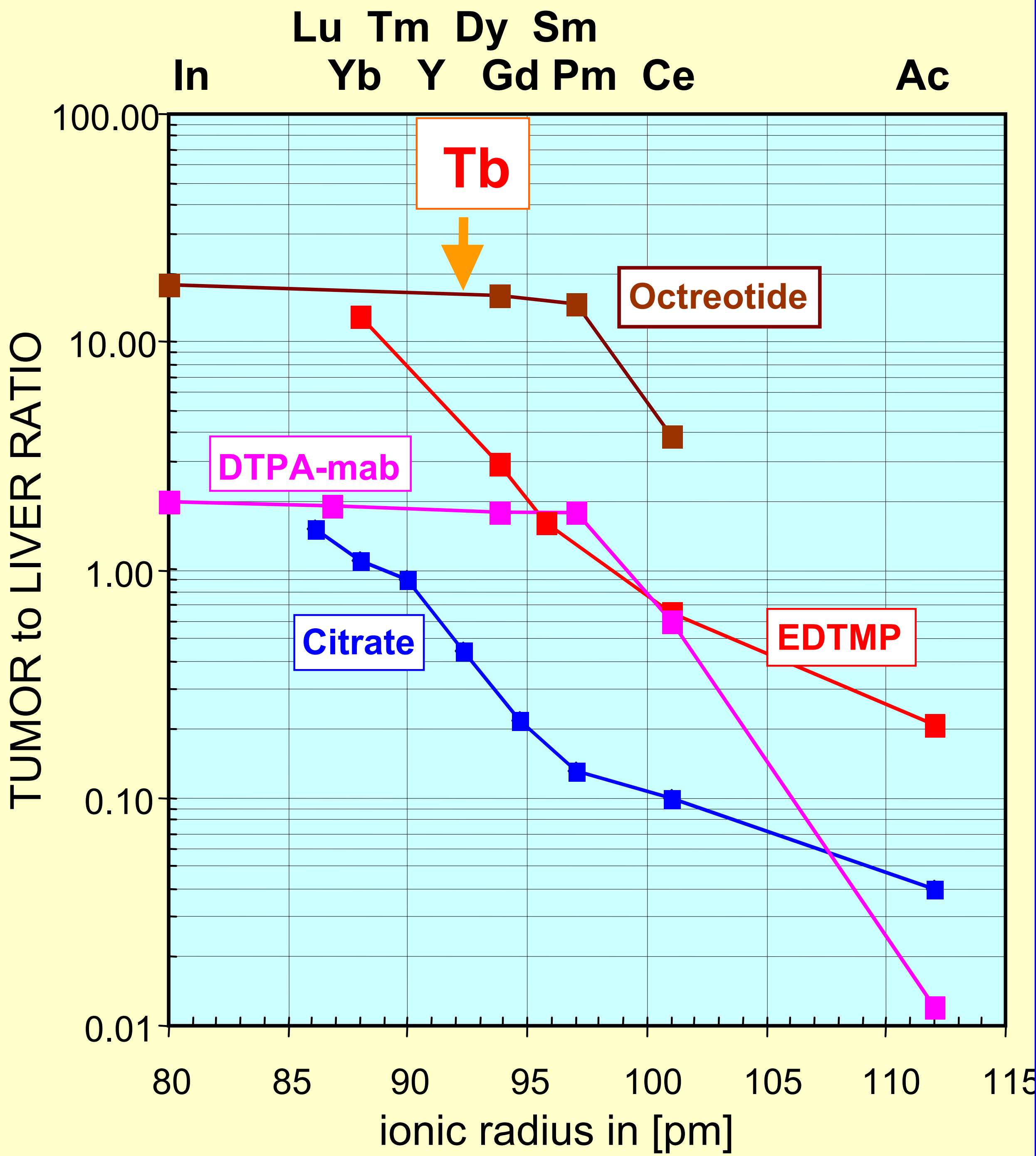
Cancer therapy with alpha emitters

- half-life
- radiotoxicity of daughter isotopes
- biokinetics: in-vivo stability of chelating agent, clearance,…
- affordable
- reliable supply: more than one facility per geographic area

GBq activity/patient sufficient!

Isotopes for targeted alpha therapy

^{149}Tb for targeted alpha therapy



Comparison

of the

bio-distribution

of different

tumor seeking tracers

labeled with

radio-lanthanides, ^{225}Ac and ^{111}In

free chelates:

Citrate

EDTMP

specific tracers:

Octreotide

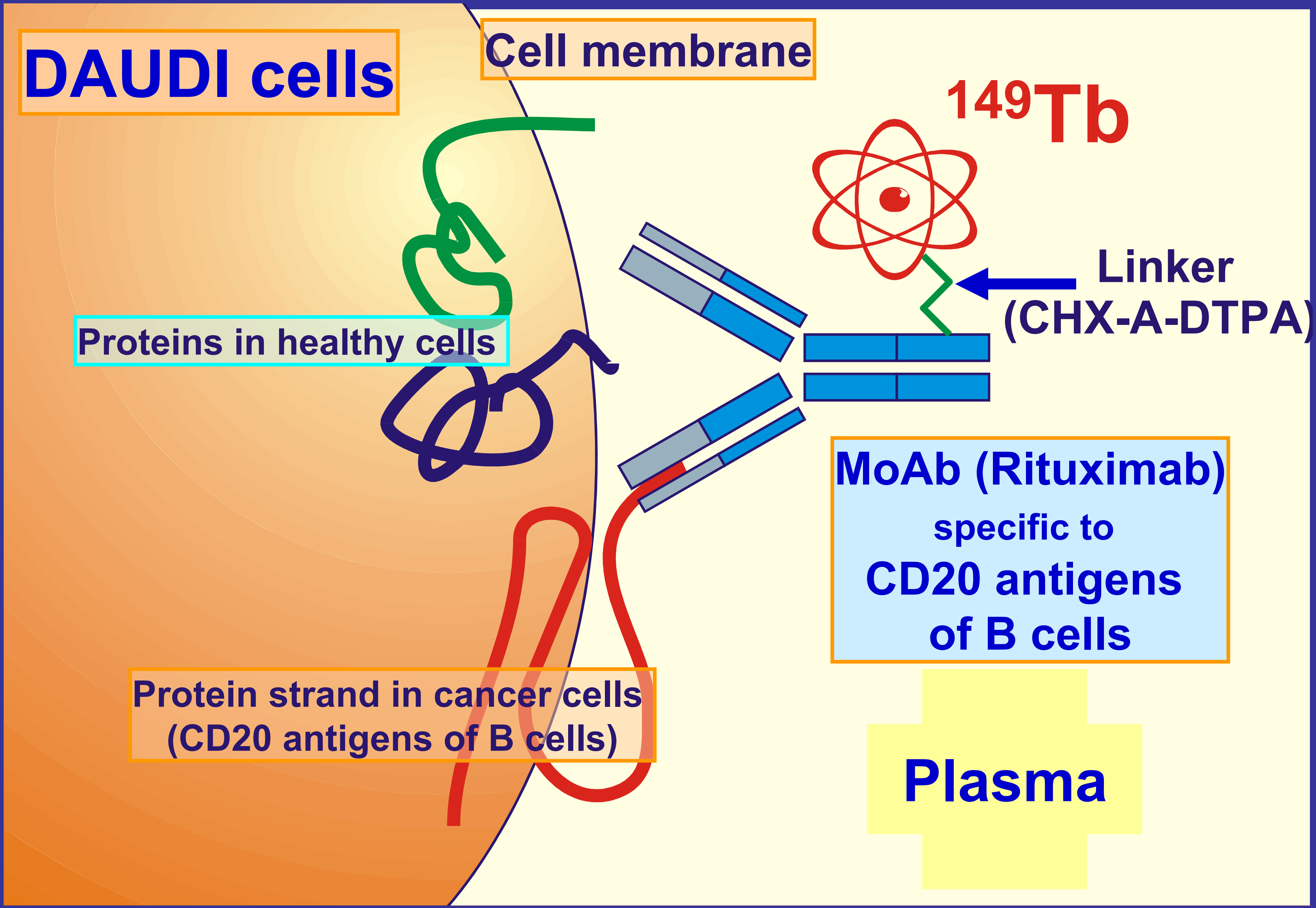
and

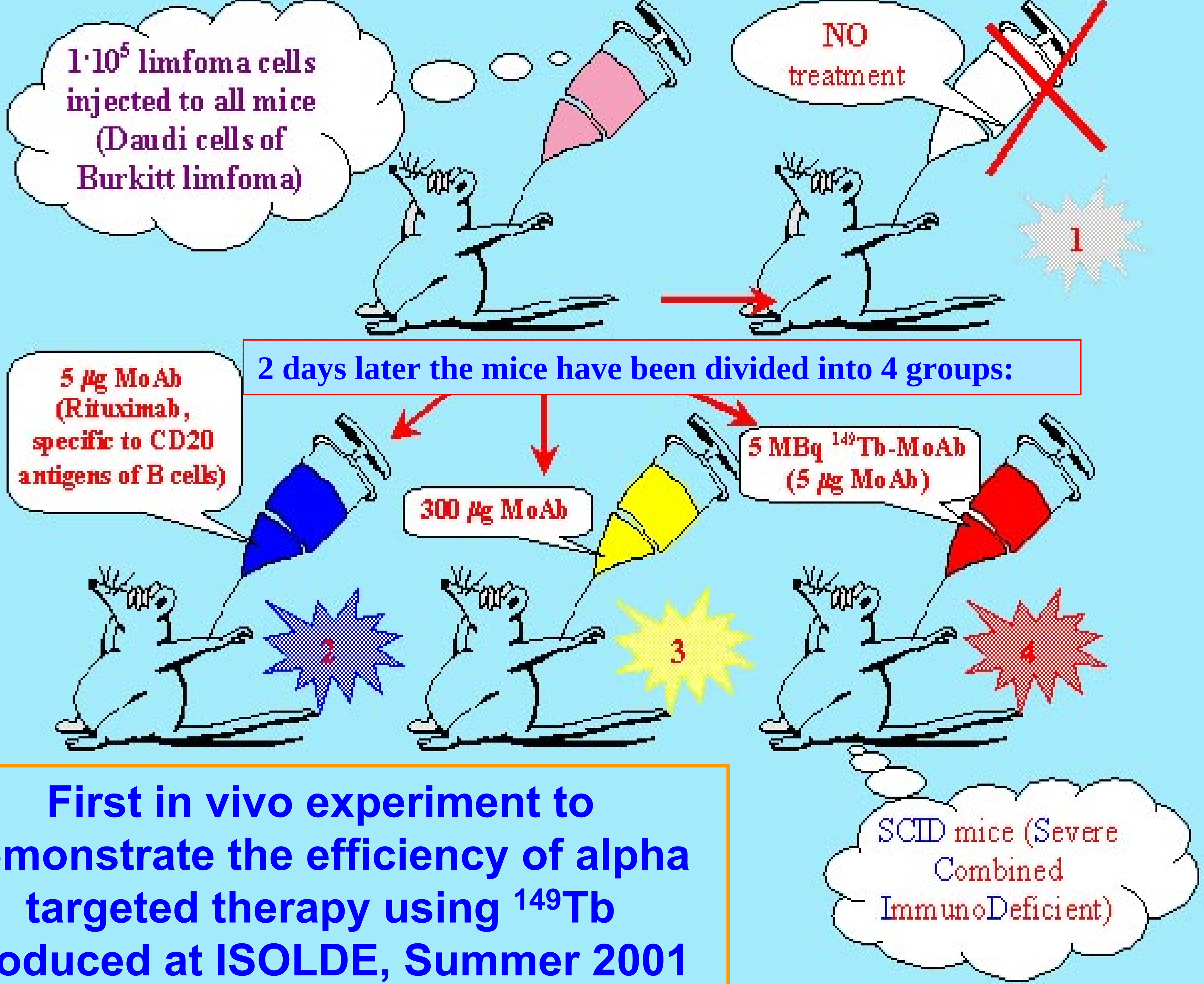
Mab

Linker: Aminobenzyl-DTPA

*G.J.Beyer, Hyperfine Interactions **129** (2000) 529.*

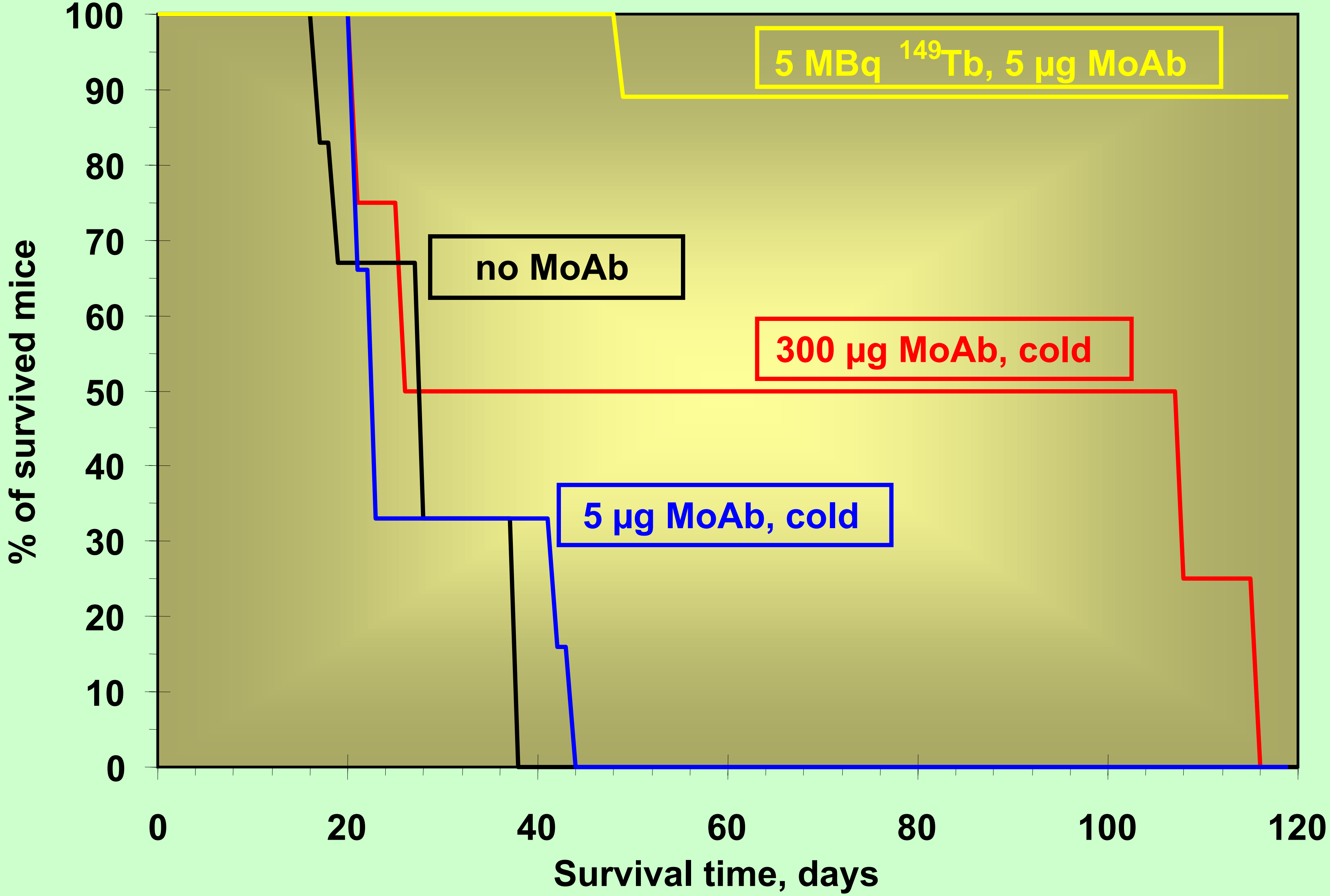
Principle of Radioimmuno Therapy





First in vivo experiment to demonstrate the efficiency of alpha targeted therapy using ^{149}Tb produced at ISOLDE, Summer 2001

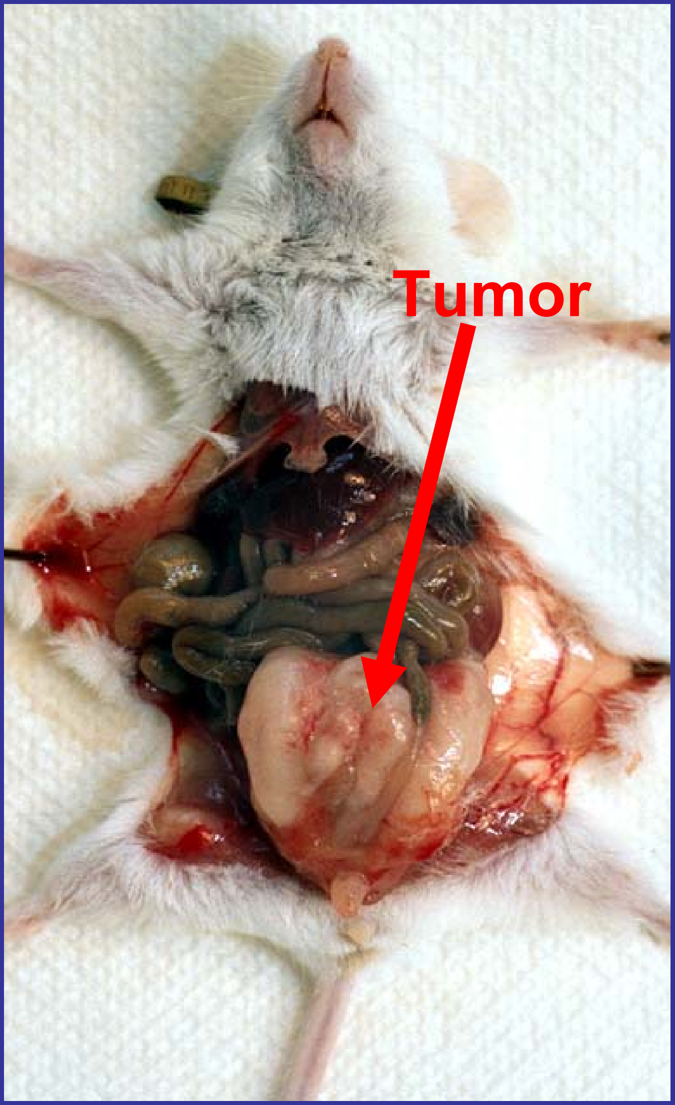
Survival of SCID mice



G.J. Beyer et al., Eur. J. Nucl. Med. Molec. Imaging ***31*** *(2004) 547.*

103 d p.i.

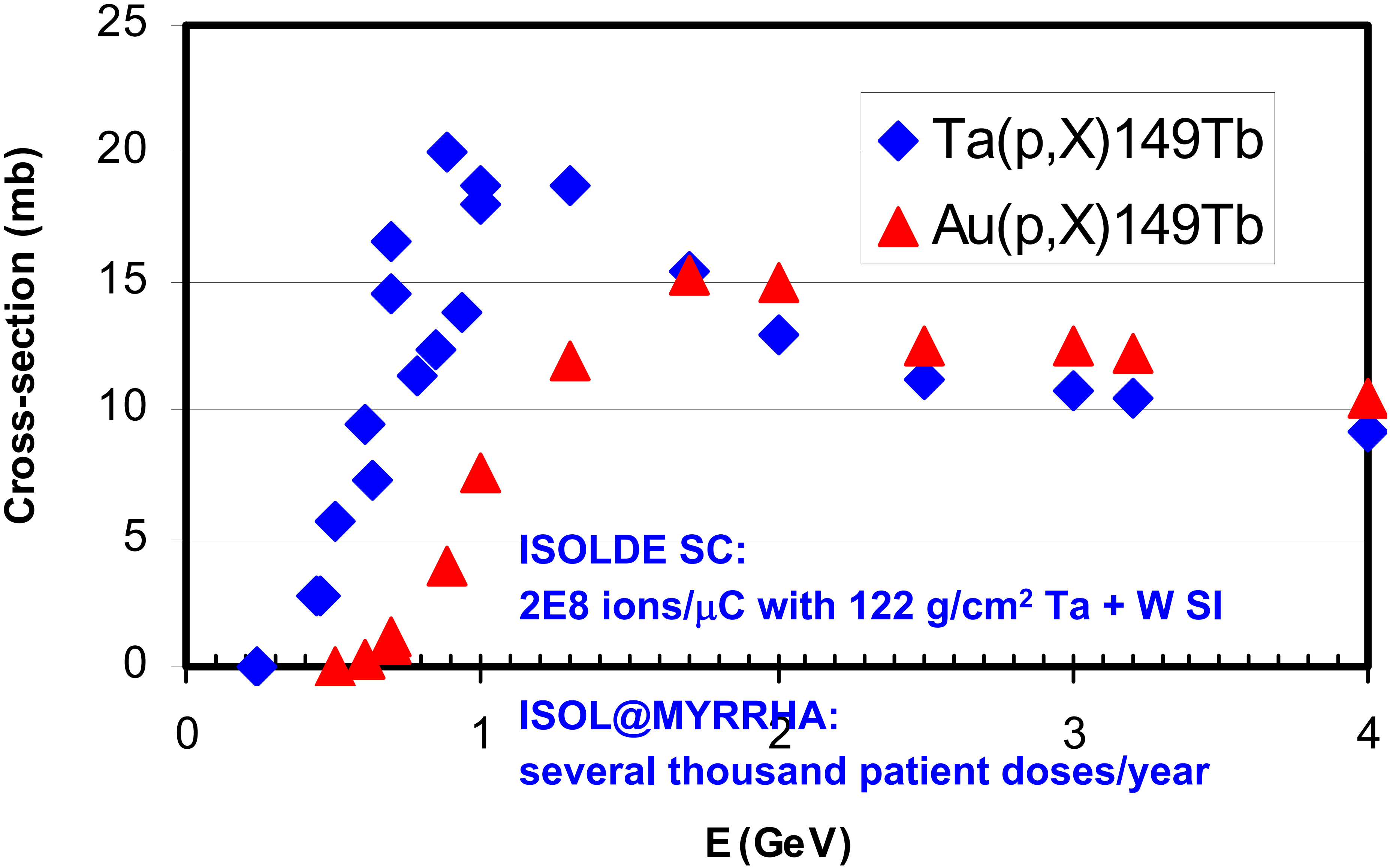
108 d p.i.



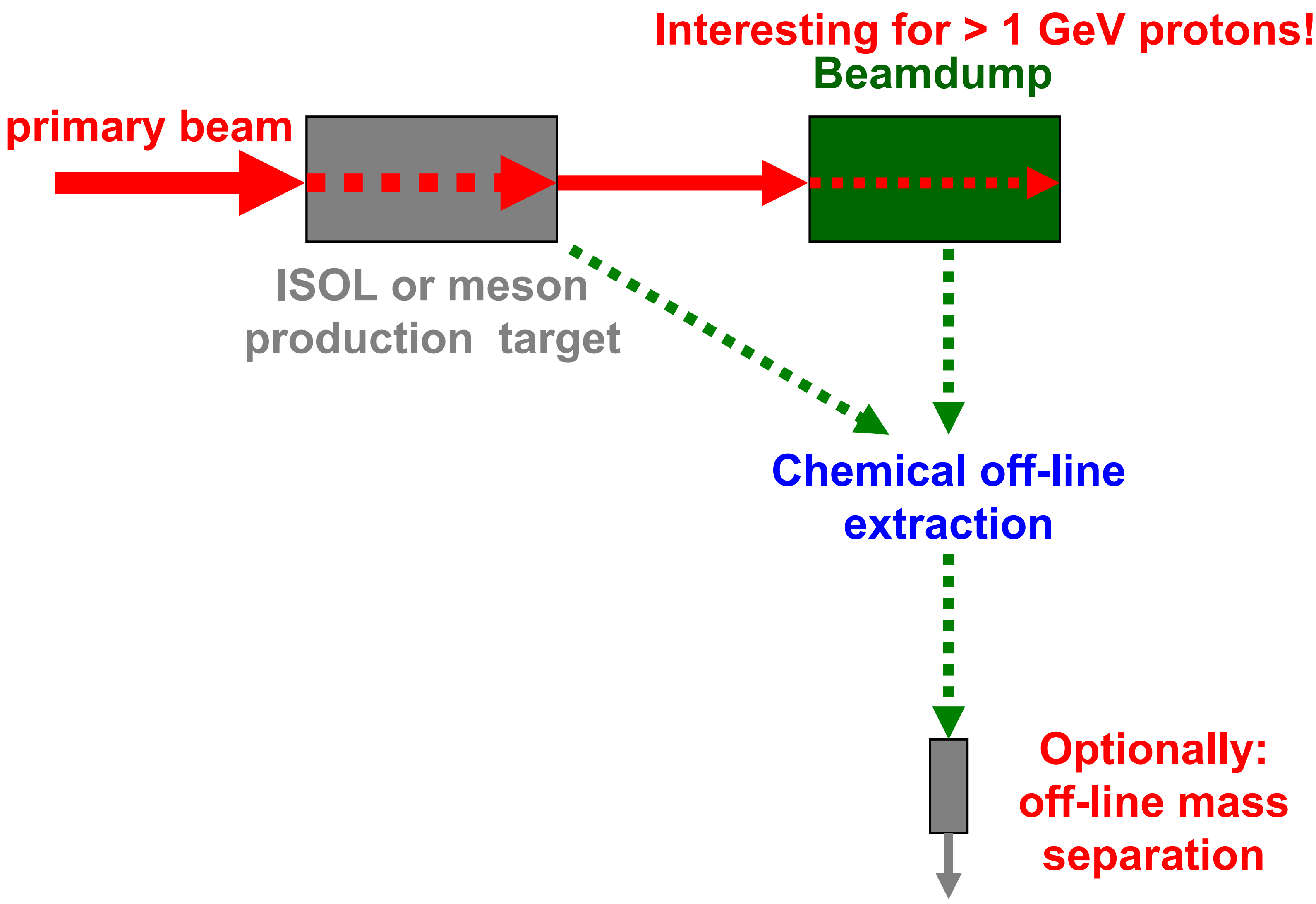
300 µg MoAb cold

5 MBq ^{149}**Tb**-MoAb (5 µg)

Spallation production of ^{149}Tb

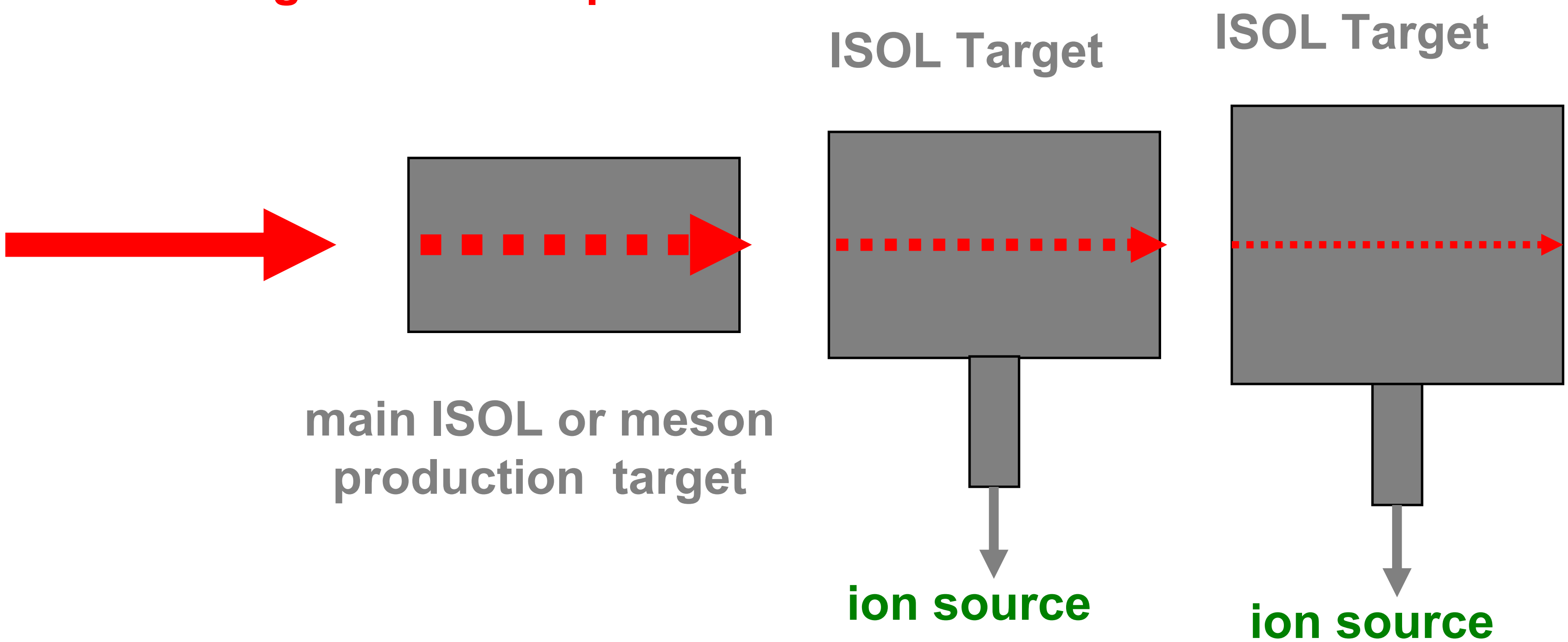


1. Off-line extraction from irradiated targets or dedicated beamdumps



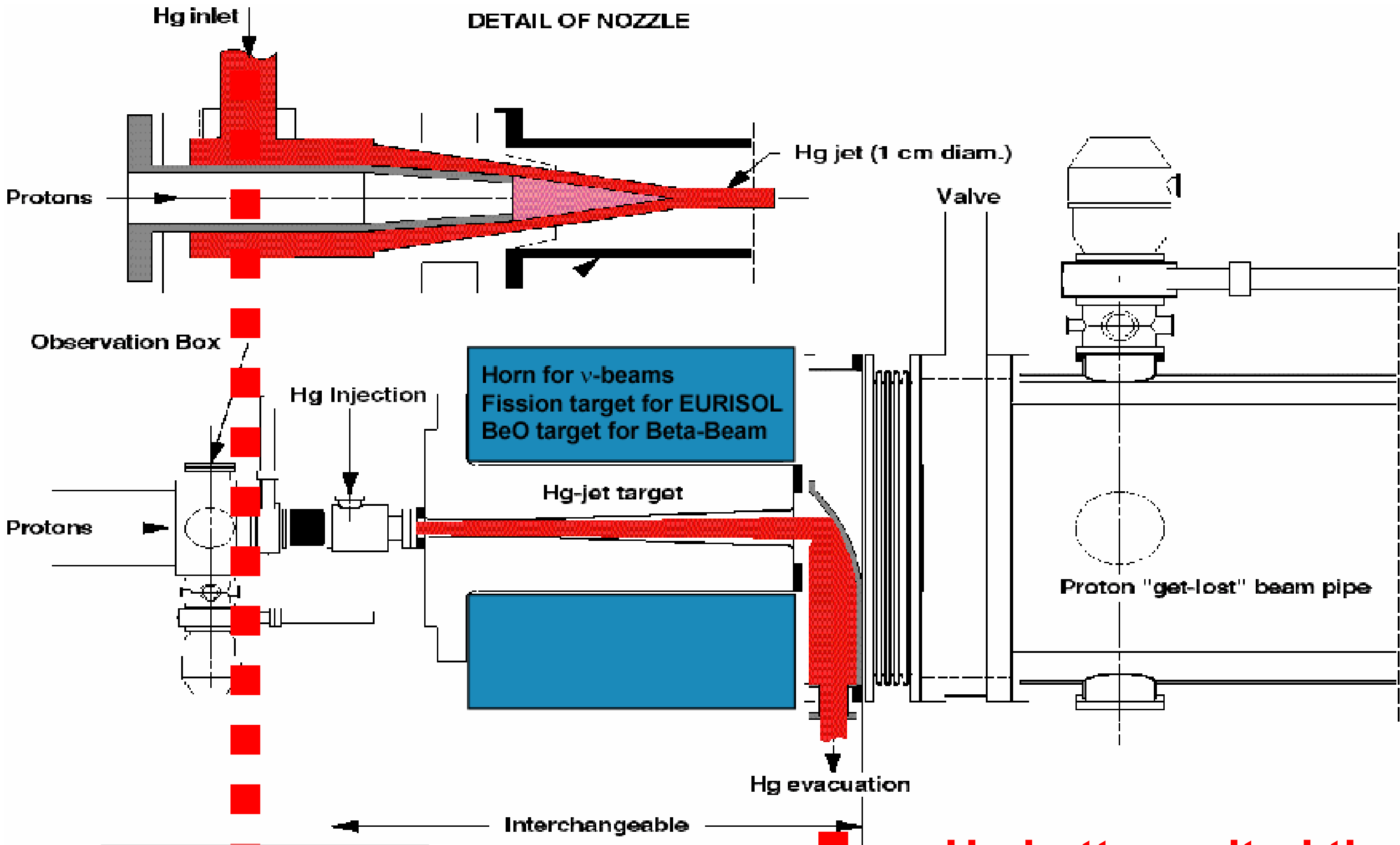
2. Dedicated ISOL target(s) at beamdump position

Interesting for > 1 GeV protons!



Extraction of mass-separated beams of short-lived isotopes for nuclear medicine

3. On-line extraction from liquid metal targets



Hg better suited than Pb/Bi!

Heat exchanger and pump

Side-loop

Chemical extraction of spallation products

Optionally:
off-line mass separation

Summary

- **powerful accelerator is not everything**
- **aim for tens of μA proton beam rather than hundreds of μA**
- **effort in instrumentation should be in relation to effort in beam production**
- **most exotic isotopes reachable for few elements only**
- **applications with limited count rate capability or detection methods with high intrinsic selectivity but low efficiency compensated by longer running times**
- **driver accelerator with low trip probability should favor experiments relying on constant beam intensity (scanning)**
- **supply of specific medical isotopes?**